PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

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Applicant(s):	Weaver et al.	
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Examiner:	Curs, Nathan M.	
Title:	CLOSED-LOOP OPTICAL NETWORK SYSTEM AND AN ASSOCIATED TRANSCEIVER AND METHOD FOR TRANSMITTING A PLURALITY OF OPTICAL SIGNALS	
Docket No.:	038190/239642	
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APPEAL BRIEF UNDER 37 CFR § 41.37

This Appeal Brief is filed pursuant to the "Notice of Appeal to the Board of Patent Appeals and Interferences" filed May 11, 2006, and following a "Notice of Panel Decision from Pre-Appeal Brief Review" of August 9, 2006.

1. ***Real Party in Interest.***

The real party in interest in this appeal is The Boeing Company, the assignee of the above-referenced patent application.

2. ***Related Appeals and Interferences.***

There are no related appeals and/or interferences involving this application or its subject matter.

3. ***Status of Claims.***

The present appeal involves all of the pending claims of the present application, namely Claims 1-26, which are presently under a final rejection as set forth by the final Official Action

of January 11, 2006. A pre-appeal request was submitted on May 11, 2006, but the decision of the panel of Examiners found that all of the pending claims stand rejected because one or more issues are ripe for appeal. The claims at issue are set forth in the attached Claims Appendix.

4. ***Status of Amendments.***

There are no unentered amendments in this application.

5. ***Summary of Claimed Subject Matter.***

Embodiments of the present invention provide a a closed-loop optical network system utilizing wavelength division multiplexing of signals in a multi-mode fiber optic infrastructure. As described and claimed in independent Claim 1, and similarly independent Claims 7 and 12, a closed-loop optical network system includes a network bus **12** for transmitting a plurality of optical signals. Pat. Appl., FIG. 1; and page 6, lines 12-14. As explained, single mode photonic networks may be expensive to implement, difficult to install and maintain, and only tolerate more benign environments. *Id.* at page 6, lines 18-29. As such, the network bus of independent Claims 1, 7 and 12 is a multi-mode network bus to thereby permit the system to support a large number of remote devices in an inexpensive and highly environmentally robust system. *Id.* at page 2, lines 21-30.

The system of independent Claim 1, and similarly independent Claims 7 and 12, further includes a multiplexer **14**, a plurality of remote devices **16** and a demultiplexer **18**. *Id.* at FIG. 1; and page 6, lines 12-14. The multiplexer is capable of wavelength division multiplexing (WDM) the plurality of input optical signals for transmission via the network bus. *Id.* at page 7, lines 20-28. In this regard, the input optical signals have a plurality of predetermined optical wavelengths. *Id.* at page 7, lines 9-10. As in dependent Claim 2, and similarly independent Claim 7, the system may further include a plurality of optical sources **22** capable of generating the plurality of input optical signals from a plurality of input electrical signals. *Id.* at page 6, lines 15-17; and page 7, lines 8-9. As in dependent Claims 3, 8 and 18, for example, the system may also include a network controller **20** for controlling communications on the network bus,

where the network controller is capable of transmitting the plurality of input electrical signals to the optical sources. *Id.* at page 6, lines 14-15; and page 6, line 30 – page 7, line 7.

As also recited by independent Claim 1, and similarly Claims 7 and 12, the remote devices are optically connected to the network bus and are capable of reading optical signals having respective predefined optical wavelengths off of the network bus. *Id.* at page 7, line 29 – page 8, line 29. The remote devices are further capable of writing optical signals having respective predefined optical wavelengths onto the network bus. *Id.* The respective predefined optical wavelengths of the signals read and written by the remote devices are at least subsets of the plurality of predetermined optical wavelengths of the optical input signals. *Id.*

The demultiplexer of independent Claim 1, and similarly independent Claism 7 and 12, can receive optical signals having at least one of the plurality of predetermined optical wavelengths from the network bus and thereafter wavelength division demultiplex the optical signals into a plurality of output optical signals. *Id.* at page 8, line 30 – page 9, line 10. As in dependent Claim 4, and similarly dependent Claim 9, for example, the system may further include a plurality of optical detectors **24** capable of receiving the plurality of output optical signals from the demultiplexer and thereafter generating a plurality of output electrical signals from the plurality of output optical signals. *Id.* at page 9, lines 4-7. The optical detectors are capable of transmitting the plurality of output optical signals to the network controller. *Id.* at page 9, lines 7-8.

One advantageous embodiment of the present invention, reflected by independent Claim 21, additionally provides a vehicle **50** adapted to support optical communications. *Id.* at FIG. 3; and page 10, lines 1-4. The vehicle includes a vehicle body **52** capable of including at least one closed-loop optical network system. *Id.* at page 10, lines 4-5. And the vehicle includes a closed-looped optical network system including a multi-mode network bus **54**, a multiplexer, a plurality of remote devices **56-64** and a demultiplexer. *Id.* at page 10, lines 5-8. The multi-mode network bus is disposed at least partially throughout the vehicle body for transmitting a plurality of optical signals. *Id.* at page 10, lines 11-13.

6. ***Grounds of Withdrawal/Rejection to be Reviewed on Appeal.***

Currently, Claims 1-20 stand rejected under 35 U.S.C. § 103(a) as being unpatentable over U.S. Patent No. 5,717,795 to Sharma et al., in view of the publication S.V. Kartalopoulos, *Introduction to DWDM Technology: Data in a Rainbow*, IEEE Press 41, 42 (2000). The remaining claims, namely Claims 21-26, currently stand rejected under 35 U.S.C. § 103(a) as being unpatentable over Sharma in view of U.S. Patent No. 4,089,584 to Polczynski, and further in view of Kartalopoulos.

7. ***Argument.***

As explained below, Applicants respectfully submit that the claimed invention of independent Claims 1, 7, 12 and 21, and by dependency Claims 2-6, 8-11, 13-20 and 22-26, is patentably distinct from Sharma, Kartalopoulos and Polczynski, taken individually, and that Sharma and Kartalopoulos cannot properly be combined. Thus, Applicants respectfully request that the rejections be reversed.

I. Claims 1-20 are Patentable over Sharma/Kartalopoulos

The primary reference cited against the claimed invention, Sharma, discloses an optical wavelength division multiplexed network system that permits optical communications between any of a plurality of nodes via a main trunk line. As disclosed, the network system includes a plurality of nodes interconnected by an optical fiber in a ring form and includes a multi-wavelength light source for multiplexing and transmitting a plurality of lights having different wavelengths. Each of the nodes includes an add-drop multiplexer for extracting light of a particular wavelength among the lights of a plurality of wavelengths transmitted via the main trunk line into the node, and for inserting the light of the preset wavelength from the node into the main trunk line. Each node also includes at least one optical receiver for receiving part of the light extracted by the add-drop multiplexer, and a modulator for modulating light extracted by add-drop multiplexer with data to be transmitted and sending the light back to the add-drop multiplexer and on to the main trunk line.

Independent Claim 1 of the present application provides a closed-loop optical network system. As recited, the system includes a multi-mode network bus for transmitting a plurality of optical signals, and a multiplexer capable of wavelength division multiplexing a plurality of input optical signals for transmission via the network bus, where the input optical signals have predetermined optical wavelengths. The system also includes a plurality of remote devices optically connected to the network bus. The remote devices are capable of reading optical signals having respective predefined optical wavelengths off of the network bus, and capable of writing optical signals having respective predefined optical wavelengths onto the network bus. In addition to the multi-mode network bus, multiplexer and remote devices, the system of independent Claim 1 also includes a demultiplexer capable of receiving optical signals having at least one of the predetermined optical wavelengths from the network bus, and thereafter wavelength division demultiplexing the optical signals into output optical signals.

In contrast to the system of independent Claim 1, and as conceded by the first, second and now final Official Actions, Sharma does not disclose a multimode network bus. Nonetheless, the final Official Action alleges that, as Sharma discloses the use of a multimode light source, it would have been obvious to have used the multimode light source in conjunction with the other features of the system of Claim 1 since multimode light sources are less expensive than single-mode light sources. Further, the final Official Action alleges that Kartalopoulos discloses a multimode optical fiber and that such a fiber has advantages over single-mode optical fiber in splicing and light coupling. Thus, the final Official Action alleges that it would have been further obvious to one skilled in the art to implement a multimode fiber, as disclosed by Kartalopoulos, in the system disclosed by Sharma, to disclose the claimed invention. Applicants respectfully submit, however, that not only does Sharma disclosing a multimode light source not support any suggestion of a multimode network bus, but that Sharma in fact suggests a single mode network bus; and respectfully submit that one skilled in the art would not in fact have been motivated to modify Sharma to include a multimode network bus.

A. Multimode of Sharma Differs from Multimode of Claimed Invention

Applicants initially note that, as understood by those skilled in the art, multi-mode as the term is used to describe the light source in Sharma differs from multi-mode as the term is used to describe the multi-mode network bus. In this regard, Sharma discloses that the multi-mode light source emits laser light "corresponding to a plurality of longitudinal modes at a fixed wavelength interval." Sharma Patent, col. 6, ll. 42-43 (emphasis added). As readily understood by those skilled in the art, however, a multi-mode network bus transmitting optical signals, as recited by independent Claim 1, operates in multiple transverse modes. More particularly, as is well known to those skilled in the art, light sources such as lasers are capable of operating in one or more transverse modes (having a field vector normal to the direction of propagation) and one or more longitudinal modes (having a field vector parallel to the direction of propagation). By operating in multiple longitudinal modes, however, a light source is capable of producing multiple frequencies.

In contrast to light sources, network buses (waveguides, optical fibers, etc.) transmitting optical signals are typically characterized by one or more transverse modes. For each transverse mode, a standing wave is established in a direction normal to the direction of propagation, where higher mode optical signals are generally characterized by sharper guiding angles and a smaller propagation constant in the direction of propagation, as compared to lower mode optical signals. Thus, the mode of the light source disclosed by Sharma refers to the longitudinal mode to produce multiple wavelengths. In contrast, the mode of the network bus recited by independent Claim 1 refers to the transverse mode which, because the network bus is multimode (generally having a larger waveguide diameter), permits multiple standing waves to be established in a direction perpendicular to the direction of propagation.

For the sake of illustration, consider that a light source operating at multiple longitudinal modes such as in the manner disclosed by Sharma may produce light at multiple frequencies. In the visible light range of the electromagnetic spectrum, these multiple frequencies may correspond to multiple colors of light. In contrast, a multimode network bus such as that recited by the claimed invention permits propagation of multiple transverse modes, which in the case of colors of light, refers to the bus permitting propagation of multiple waves of a single color of light down the length of the bus. It should be appreciated that a multimode bus may support

multiple waves of multiple colors of light from a multimode light source. Thus, the number of longitudinal modes of a light source supported by a network bus typically does not depend on the number of transverse modes of the bus.

Applicant therefore respectfully submits that even considering the multimode light source disclosed by Sharma, Sharma does not teach or suggest a multimode network bus, as recited by independent Claim 1 of the present application. As the multimode light source of Sharma operates in multiple longitudinal modes, the multimode light source could equally provide optical signals to a single mode network bus or a multimode network bus. Thus, even if Sharma discloses a multimode light source, such disclosure does not also suggest a multimode network bus, as in the claimed invention.

B. Single-Mode Fibers in Telecommunications Systems

As explained in response to the first Official Action, Sharma does not explicitly define its network bus as being single mode or multimode. Nonetheless, Sharma does suggest that its network bus is, in fact, a single mode network bus, in contrast to the multimode network bus of independent Claim 1. In this regard, Sharma discloses the use of related network systems being proposed for optical telecommunication. As is well known to those skilled in the art, due to increased modal dispersion in multimode waveguides, optical telecommunication networks are most typically, if not exclusively, implemented using single mode waveguides. Moreover, as shown and described with respect to FIGS. 8, 9 and 10 of Sharma, the network nodes of various embodiments of the Sharma system include optical circulators (see, e.g., optical circulators **618**, **6111** of FIG. 8). And as is also well known to those skilled in the art, optical circulators are primarily used with single mode waveguides.

In response to the above remarks, the second Official Action indicated that such remarks cannot take the place of evidence in the record, and further that the Sharma patent does not disclose or suggest one type of fiber over another. Applicants respectfully submit, however, that remarks explaining that the use of multimode fibers in telecommunications applications is contrary to accepted wisdom in the art are not of the type requiring evidence in the record. *See* MPEP § 716.01(c) II. (explaining that attorney statements for which evidence is required include

"statements regarding unexpected results, commercial success, solution of a long-felt need, inoperability of the prior art, invention before the date of the reference, and allegations that the author(s) of the prior art derived the disclosed subject matter from the applicant").

Applicants respectfully submit that the totality of the prior art suggests that the use of multimode fibers in telecommunications systems is contrary to accepted wisdom in the art. As disclosed in column 1, lines 40-45 of U.S. Patent No. 4,776,655 to Robertson, for example, the majority of optical fiber used in telecommunications as of 1985 (i.e., the foreign priority filing date of the Robertson patent) was monomode (i.e., single mode) optical fiber. In this regard, one of the principle problems with the use of multimode optical fibers for telecommunications is the limit modal dispersion imposes on the information carrying capacity of such fibers. *See* U.S. Patent No. 3,957,343 to Dyott et al., column 1, lines 18-21 (foreign priority filing date of 1972). As explained in U.S. Patent No. 5,011,247 to Boudreau et al. (filed 1990), "[m]any telecommunications applications use single-mode optical fiber because of the superior bandwidth arising from its reduction of mode partition noise.... Multimode optical fiber is of little value for telecommunications because it suffers from mode-partition noise when used for high speed transmissions over a distance." Column 1, lines 37-46. *See also* U.S. Patent Nos. 4,957,342 (column 1, lines 46-62) and 5,024,504 (column 1, lines 36-51) both to Boudreau et al. (and further explaining that technology for aligning multimode optical fibers in an array is not acceptable for telecommunications).

In the final Official Action and during a telephone interview with the Examiner, the Examiner cited Kartalopoulos as disclosing multimode fibers having a bandwidth of up to 100 Mbps for lengths up to 40 km, and asserted that this disclosure supported the use of multimode fiber in telecommunications systems. To the contrary, however, Applicants respectfully submit that merely citing bandwidth and length capabilities of multimode fiber does not itself support their use in telecommunications systems, particularly without comparison to corresponding bandwidth and length characteristics of telecommunications systems. Applicants respectfully submit that nothing in Kartalopoulos teaches or suggests use of multimode fibers in telecommunications systems. In a number of passages, however, Kartalopoulos does suggest use of single mode fiber in telecommunications applications, particularly noting that, in contrast to

the multimode fiber characteristics noted by the Examiner, single mode fiber is suitable for transmitting signals at 40 Gb/s (or higher) and up to 200 km without amplification (Kartalopoulos, page 42). See, for example, the following passages:

> "For long haul transmission, single-mode fibers ... have been engineered and manufactured." Kartalopoulos, page 50.
>
> "[M]any telecommunications companies, new and old, install many thousands of kilometers of fiber each year...." *Id.* at page 69 (emphasis added).
>
> "Transporting SONET OC-192 (or SDH STM-64) signals at 10 Gb/s over single-mode fiber has become a technology of the past. Transporting OC-768 at 40 Gb/s over single-mode fiber for 100 km is an advanced technology that is becoming readily available. At 40 Gb/s, half-a-million simultaneous telephone conversations can be transmitted." *Id.* at page 177 (emphasis added).

Also during the telephone interview, the Examiner explained that the aforementioned prior art references cited by Applicants were given little weight by the Examiner in demonstrating the preferred and typical use of single-mode fiber in telecommunications systems due to the relative age of those references as compared to Kartalopoulos. Accordingly, Applicants draw further attention to U.S. Patent No. 6,334,019 to Birks et al. (filed 1999), U.S. Patent No. 7,031,612 to Liou et al. (filed 2001), and U.S. Patent No. 6,754,423 to Simons et al. (filed 2001). Consistent with the prior art previously cited by Applicants, Birks explains that single-mode fibers are advantageous over multimode fibers in telecommunication systems due to their avoiding the problem of intermodal dispersion suffered by multimode fibers. Column 1, line 58 – column 2, line 2. Liou explains that although a LAN (local area network) may be either multimode or single mode, fiber for long distance applications such as telecommunications applications must be single-mode fiber. And Simons explains that single mode fibers are mainly applied in the field of telecommunications due to their low attenuation and dispersion characteristics. Column 1, lines 22-39. Further, and with respect to the Examiner's assertion of multimode fibers spanning 40 km supports their use in telecommunications, Simons explains that such long-distance links often span many thousands of kilometers, in contrast to the 40 km length given by Kartalopoulos. *Id.* at lines 29-31.

Applicants again respectfully submit that considering the totality of the prior art, the use of multimode optical fiber in telecommunications systems is contrary to accepted wisdom in the art. As the Sharma system is disclosed with reference to telecommunications systems, Sharma thereby suggests its network bus is a single-mode network bus, as opposed to a multimode network bus, as in the claimed invention.

C. Combination of Sharma/Kartalopoulos

Even considering Applicants argument that Sharma does not teach or suggest a particular type of optical fiber, the second Official Action alleges that Kartalopoulos discloses multimode fiber, and that it would have been obvious to one skilled in the art to combine the teachings of Kartalopoulos with Sharma to disclose the claimed invention. Applicants respectfully submit, however, that one skilled in the art would not be motivated to modify Sharma to include the multimode fiber of Kartalopoulos. In this regard, as explained above, the Sharma system is disclosed with reference to telecommunications systems, and the use of multimode fiber in telecommunications systems is contrary to accepted wisdom in the art. Sharma therefore teaches away from the use of multimode fiber, such as that disclosed by Kartalopoulos, in the disclosed telecommunication system. *See* MPEP § 2145 X.D.2. (explaining that "[i]t is improper to combine references where the references teach away from their combination").

As motivation for including the multimode fiber of Kartalopoulos in the system of Sharma, the final Official Action explains that multimode fiber is easier to splice and couple light into, as compared to single-mode fiber. Applicants respectfully submit, however, that even considering the general benefit of multimode fiber over single-mode fiber, finding a motivation to combine references requires <u>weighing all of the benefits, both lost and gained, of combining references</u>. *Winner Int'l Royalty Corp. v. Ching-Rong Wang*, 202 F.3d 1340, 1349 & n.8 (Fed. Cir. 2000). In this regard, a motivation to combine requires finding what, on balance, is desirable as opposed to what is feasible. *Id.* In the instant case, the benefits of multimode fiber over single-mode fiber proffered by the Examiner exist by virtue of their construction and have existed since the user of fiber optics in telecommunications. Yet as demonstrated by the aforementioned references cited by Applicants, telecommunication systems still predominately,

if not exclusively, employ single-mode fiber. And as such, Applicants respectfully submit that, at least in so far as the telecommunications industry has implemented fiber optics, on balance, one skilled in the art would not be motivated to include the multimode fiber of Kartalopoulos in the telecommunications system of Sharma due to the ease of splicing and light coupling of multimode fiber.

For at least the foregoing reasons, Applicants respectfully submit that independent Claim 1, and by dependency Claims 2-6, is patentably distinct from Sharma and Kartalopoulos, taken individually; and that Sharma and Kartalopoulos cannot properly be combined. Applicants also respectfully submit that independent Claims 7 and 12 recite subject matter similar to that of independent Claim 1, including the aforementioned closed-loop network system with a multimode network bus for transmitting optical signals. Thus, Applicants also respectfully submit that the independent Claims 7 and 12, and by dependency Claims 8-11 and 13-20, are also patentably distinct from Sharma and Kartalopoulos, taken individually, and that Sharma and Kartalopoulos cannot properly be combined, for at least the same reasons given above with respect to independent Claim 1.

II. Claims 21-26 are Patentable over Sharma/Polczynski/Kartalopoulos

As indicated above, Claims 21-26 currently stand rejected as being unpatentable over Sharma, in view of Polczynski and further in view of Kartalopoulos. Independent Claim 21 recites a vehicle adapted to support optical communications. As recited, the vehicle includes a vehicle body and a closed-loop optical network system. The closed-loop optical network system includes a network bus and a plurality of remote devices disposed at least partially throughout the vehicle. Similar to independent Claim 1, the network bus comprises a multi-mode network bus for transmitting a plurality of optical signals, and remote devices are capable of reading optical signals having respective predefined optical wavelengths off of the network bus, and capable of writing optical signals having respective predefined optical wavelengths onto the network bus. Also similar to independent Claim 1, the network system includes a multiplexer capable of wavelength division multiplexing a plurality of input optical signals for transmission via the network bus, and a demultiplexer capable of receiving optical signals having at least one

of the predetermined optical wavelengths from the network bus, and thereafter wavelength division demultiplexing the optical signals into output optical signals.

In contrast to independent Claim 21, and for at least the same reasons given above with respect to independent Claim 1, Applicants respectfully submit that Sharma and Kartalopoulos, taken individually or in any proper combination, do not teach or suggest a closed-loop network system with a multimode network bus for transmitting optical signals. Similarly, Applicants further respectfully submit that Polczynski does not teach or suggest the aforementioned closed-loop network system of independent Claim 21. Applicants therefore respectfully submit that independent Claim 21, and by dependency Claims 22-26, is patentably distinct from Sharma, Polczynski and Kartalopoulos, taken individually or in any proper combination.

8. ***Claims Appendix.***

The claims currently on appeal are as follows:

1. (Original) A closed-loop optical network system comprising:

a multi-mode network bus for transmitting a plurality of optical signals;

a multiplexer capable of wavelength division multiplexing a plurality of input optical signals for transmission via the network bus, wherein the plurality of input optical signals have a plurality of predetermined optical wavelengths;

a plurality of remote devices optically connected to the network bus, wherein said plurality of remote devices are capable of reading optical signals having respective predefined optical wavelengths off of the network bus, and wherein said plurality of remote devices are further capable of writing optical signals having respective predefined optical wavelengths onto the network bus; and

a demultiplexer capable of receiving optical signals having at least one of the plurality of predetermined optical wavelengths from the network bus and thereafter wavelength division demultiplexing the optical signals into a plurality of output optical signals.

2. (Original) A closed-loop optical network system according to Claim 1 further comprising a plurality of optical sources capable of generating the plurality of input optical signals from a plurality of input electrical signals.

3. (Original) A closed-loop optical network system according to Claim 2 further comprising a network controller for controlling communications on the network bus, wherein said network controller is capable of transmitting the plurality of input electrical signals to said plurality of optical sources.

4. (Original) A closed-loop optical network system according to Claim 1 further comprising a plurality of optical detectors capable of receiving the plurality of output optical signals from said demultiplexer and thereafter generating a plurality of output electrical signals from the plurality of output optical signals.

5. (Original) A closed-loop optical network system according to Claim 4, wherein said plurality of optical detectors are capable of transmitting the plurality of output electrical signals to a network controller.

6. (Original) A closed-loop optical network system according to Claim 1, wherein said plurality of remote devices read and write optical signals having respective predefined optical wavelengths that are at least subsets of the plurality of predetermined optical wavelengths of the optical input signals.

7. (Original) A transceiver for transmitting input optical signals to and receiving output optical signals from a plurality of remote devices via a multi-mode network bus in a closed-loop optical network system, said transceiver comprising:

a plurality of optical sources capable of generating the plurality of input optical signals from a plurality of input electrical signals;

a multiplexer capable of wavelength division multiplexing a plurality of input optical signals for transmission via the network bus, wherein the plurality of input optical signals have a plurality of predetermined optical wavelengths that are selectively received by respective remote devices; and

a demultiplexer capable of receiving optical signals having at least one of the plurality of predetermined optical wavelengths from the network bus and thereafter wavelength division demultiplexing the optical signals into a plurality of output optical signals.

8. (Original) A transceiver according to Claim 7, wherein said plurality of optical sources are capable of communicating with a network controller, wherein the network controller is capable of transmitting the plurality of input electrical signals to said plurality of optical sources.

9. (Original) A transceiver according to Claim 7 further comprising a plurality of optical detectors capable of receiving the plurality of output optical signals from said demultiplexer and thereafter generating a plurality of output electrical signals from the plurality of output optical signals.

10. (Original) A transceiver according to Claim 9, wherein the plurality of optical detectors of said receiving element are capable of transmitting the plurality of output electrical signals to a network controller.

11. (Original) A transceiver according to Claim 7, wherein plurality of remote devices read and write optical signals having predefined optical wavelengths that are associated with the plurality of predetermined optical wavelengths of the optical input signals.

12. (Original) A method of transmitting a plurality of optical signals over a multi-mode network bus in a closed-loop network system, said method comprising the steps of:

transmitting a plurality of input optical signals via the network bus, wherein transmitting comprises wavelength division multiplexing the plurality of input optical signals for transmission via the network bus such that the plurality of input optical signals have a plurality of predetermined optical wavelengths;

communicating with a plurality of remote devices optically connected to the network bus, wherein said communicating comprises reading optical signals having respective predefined optical wavelengths off of the network bus; and

receiving optical signals having at least one of the plurality of predetermined optical wavelengths from the network bus and thereafter wavelength division demultiplexing the optical signals into a plurality of output optical signals.

13. (Original) A method according to Claim 12, wherein communicating further comprises writing optical signals having respective predefined optical wavelengths onto the network bus.

14. (Original) A method according to Claim 13, wherein writing optical signals comprises writing optical signals having respective predefined optical wavelengths that are at least a subset of the plurality of predetermined optical wavelengths of the optical input signals.

15. (Original) A method according to Claim 12 further comprising generating the plurality of input optical signals from a plurality of input electrical signals, wherein said generating occurs before transmitting the plurality of input optical signals.

16. (Original) A method according to Claim 15 further comprising producing the plurality of input electrical signals before generating the plurality of input optical signals.

17. (Original) A method according to Claim 12, wherein receiving further comprises generating a plurality of output electrical signals from the plurality of output optical signals after wavelength division demultiplexing the composite optical signal.

18. (Original) A method according to Claim 17, wherein generating the plurality of output electrical signals further comprises transmitting the plurality of output optical signals to a network controller after generating the output electrical signals.

19. (Original) A method according to Claim 12, wherein communicating comprises reading optical signals having a plurality of predefined optical wavelengths that are at least a subset of the plurality of predetermined optical wavelengths of the optical input signals.

20. (Original) A method according to Claim 12, wherein receiving the optical signals comprises receiving the optical signals after transmission about a closed loop on the network bus from a transmitter to a receiver.

21. (Original) A vehicle adapted to support optical communications comprising:

a vehicle body; and

a closed-looped optical network system comprising:

a multi-mode network bus disposed at least partially throughout said vehicle body for transmitting a plurality of optical signals;

a multiplexer capable of wavelength division multiplexing a plurality of input optical signals for transmission via the network bus, wherein the plurality of input optical signals have a plurality of predetermined optical wavelengths;

a plurality of remote devices optically connected to the network bus and disposed at least partially throughout said vehicle body, wherein said plurality of remote devices are capable of reading optical signals having respective predefined optical wavelengths off of the network bus, and wherein said plurality of remote devices are further capable of writing optical signals having respective predefined optical wavelengths onto the network bus; and

a demultiplexer capable of receiving optical signals having at least one of the plurality of predetermined optical wavelengths from the network bus and thereafter wavelength division demultiplexing the optical signals into a plurality of output optical signals.

22. (Original) A vehicle according to Claim 21, wherein said closed-loop optical network system further comprises a plurality of optical sources capable of generating the plurality of input optical signals from a plurality of input electrical signals.

23. (Original) A vehicle according to Claim 22, wherein said closed-loop optical network system further comprises a network controller for at least partially controlling communications on the network bus within said vehicle body, wherein said network controller is capable of transmitting the plurality of input electrical signals to said plurality of optical sources.

24. (Original) A vehicle according to Claim 21, wherein said closed-loop optical network system further comprises a plurality of optical detectors capable of receiving the

plurality of output optical signals from said demultiplexer and thereafter generating a plurality of output electrical signals from the plurality of output optical signals.

25. (Original) A vehicle according to Claim 24, wherein the plurality of optical detectors of said closed-loop optical network system are capable of transmitting the plurality of output electrical signals to a network controller.

26. (Original) A vehicle according to Claim 21, wherein the plurality of remote devices of said closed-loop optical network system read and write optical signals having respective predefined optical wavelengths that are at least subsets of the plurality of predetermined optical wavelengths of the optical input signals.

9. ***Evidence Appendix.***

S.V. Kartalopoulos, *Introduction to DWDM Technology: Data in a Rainbow*, IEEE Press 42, 50, 69, 177 (2000)

U.S. Patent No. 4,776,655 to Robertson

U.S. Patent No. 3,957,343 to Dyott et al.

U.S. Patent No. 5,011,247 to Boudreau et al.

U.S. Patent No. 4,957,342 Boudreau et al.

U.S. Patent No. 5,024,504 Boudreau et al.

U.S. Patent No. 6,334,019 to Birks et al.

U.S. Patent No. 7,031,612 to Liou et al.

U.S. Patent No. 6,754,423 to Simons et al.

10. ***Related Proceedings Appendix.***
None.

CONCLUSION

For at least the foregoing reasons, Applicants respectfully request that the rejections be reversed.

Respectfully submitted,

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mode TE_{11} (also known as HE_{11}) or higher modes. Fibers that support many modes are known as *multimode*, and those that support one (the HE_{11}) are known as *single mode.* A single-mode fiber supports transmission along its longitudinal axis (HE_{11}).

Modes may be thought of as specific path eigendirections. The number of modes, M, of a multimode fiber with a step index profile (n_{core}, n_{clad}) is approximated by

$$\left\{\frac{(4\pi/\lambda)\, d\, [(n_{core}{}^2 - n_{clad}{}^2)]^{1/2}}{2}\right\}^2$$

where λ is the wavelength, and d is the core diameter.

Multimode and single-mode fibers have different manufacturing processes, different refractive index profiles, different dimensions, and therefore different transmission characteristics. Consequently, in optical transmission they find different applications. Some of the salient characteristics of multimode graded-index and single-mode fibers are summarized next.

3.4.1 Multimode Graded Index

The multimode graded index process has the following properties.

- It minimizes delay spread, although the delay is still significant.
- A 1% index difference between core and cladding amounts to a 1–5 ns/km delay spread (compare with step index, which has about 50 ns/km).
- It is easy to splice and to couple light into.
- The bit rate is limited: up to 100 Mb/s for lengths up to 40 km; shorter lengths support higher bit rates.
- Fiber span without amplification is limited: up to 40 km at 100 Mb/s (extended to Gb/s for shorter distances for graded index).

3.4.2 Single Mode

The single-mode process has the following properties.

- It (almost) eliminates delay spread.
- It is more difficult to splice and to exactly align two fibers together.
- It is more difficult to couple all photonic energy from a source into it.
- It is difficult to study propagation with ray theory: Maxwell's equations are required.
- It is suitable for transmitting modulated signals at 40 Gb/s (or higher) and up to 200 km without amplification.

However, $\partial\tau/\partial\omega = L\beta''$ and $\partial\omega/\partial\lambda = -2\pi\nu/\lambda^2$ and thus,

$$D = -\frac{2\pi\nu}{\lambda^2}\beta''$$

and

$$\Delta\tau = DL\left[\left(\frac{-1}{2\pi\nu/\lambda^2}\right)\right]\Delta\omega.$$

Finally, the pulse spread, or chromatic dispersion, is expressed by

$$\Delta\tau = |D|L\Delta\lambda,$$

where ∂ has been replaced by Δ and $\Delta\lambda$ is the optical spectral width of the signal (in nm units); chromatic dispersion is also denoted by the Greek letter σ (Figure 3.13).

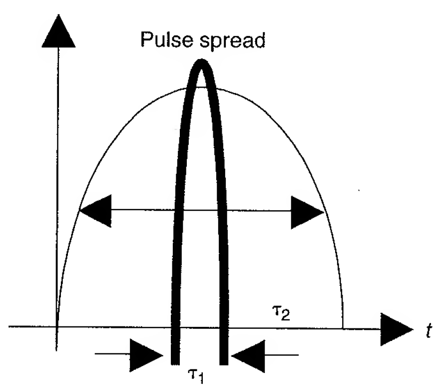

Figure 3.13 Pulse spread due to chromatic dispersion.

3.13 DISPERSION-SHIFTED AND DISPERSION-FLATTENED FIBERS

The dependency of the refractive index of silica fiber is nonlinear. As such, at some wavelength, the derivative $d\{n(\omega)\}/d\lambda$ becomes zero; that is, material dispersion becomes zero. The wavelength where the derivative is zero is called *zero-dispersion wavelength.*

A conventional single-mode fiber with a core diameter of about 8.3 μm and an index of refraction variation of about 0.37% has a zero dispersion at about 1.3 μm. Below this point, wavelength dispersion is negative and above it is positive.

For long-haul transmission, single-mode fibers with specialized index of refraction profiles (by controlling the dopant) have been engineered and manufactured.

A fiber with a zero-dispersion point shifted at 1550 nm (1.55 μm) (i.e., where the minimum absorption for silica fiber is) is called *dispersion-shifted fiber* (DSF). These fibers are compatible with optical amplifiers that perform best at around 1550 nm. Dispersion-shifted fiber with low loss in the *L-band* (1570–1610 nm) provides a wide range of wavelengths making it suitable for DWDM applications. For example, DSF fiber has been installed extensively in Japan.

- The two fiber ends to be connected should be treated so that the end faces are flat, perpendicular to the fiber longitudinal axis, and highly polished (or forming a spherical lens).
- The two end faces should be treated with antireflective coatings.
- The two fiber cores should be in perfect alignment.
- The two end faces should be brought into close proximity.

The first two precautions are related to the treatment of fiber ends and are accomplished with specialized abrasive materials and coatings. The third is related to how well the fiber has been manufactured (i.e., whether the core is exactly at the center of the circular fiber) and how well interconnecting devices align the cores. The concentricity error of single-mode fiber (based on ITU-T G.652) should be less than 1 μm. The cores are accurately aligned with biconical self-aligned connectors or aligned grooves. Finally, the last item is related to the flatness and perpendicularity of the two end surfaces and to the accuracy of the connectors.

In any case, connector optical power loss must be taken into serious account when one is estimating the overall power loss of an optical link. Because of the stringent power loss budget, fibers are installed preferably in segments many kilometers long, to minimize the number of interconnecting devices.

3.30 CONCLUSION

The quest for a fiber cable that introduces the least optical loss across a wide spectrum of wavelengths, the least dispersion, and almost no nonlinear effects still challenges fiber-optic designers and manufacturers.

However, although the transmission characteristics of fiber cable have been greatly improved, older fibers are still being used. In addition, there is a large variation in fiber specifications among both fiber cables and manufacturers. Clearly, this adds another level of complexity to the design challenges of optical systems, which must be compatible with fibers and vendor equipment of all types. Cost-effectiveness is another important consideration.

Fiber cable as a transmission medium has many highly advantageous qualities. Thus, many telecommunications companies, new and old, install many thousands of kilometers of fiber each year in the ground, along bridges and highways, through high-rise buildings, through natural-gas pipes, along rivers, by train rails, and under the oceans, interconnecting continents, countries, cities, and homes. Thus, one can deduce conclusively that the future of fiber is truly very bright.

PART IV
DENSE WAVELENGTH DIVISION MULTIPLEXING

Transporting SONET OC-192 (or SDH STM-64) signals at 10 Gb/s over single-mode fiber has become a technology of the past. Transporting OC-768 at 40 Gb/s over single-mode fiber for 100 km is an advanced technology that is becoming readily available. At 40 Gb/s, half-a-million simultaneous telephone conversations can be transmitted. Transporting above 40 Gb/s is the next challenge. Although such rates may seem more than adequate, combined voice and data traffic (video, Internet, etc.) may require yet more bandwidth in a single fiber. Thus, some reasonable questions are: What is the upper bandwidth limit in a fiber? At what point will optoelectronic (transmitter, receiver) devices reach their limit? Does this mean that optical fiber is approaching a maximum bandwidth capacity?

Advances in laser and optoelectronic device technology have made it possible to transmit more than one wavelength in the same fiber. This practice is known as *wavelength division multiplexing* (WDM). Adding wavelengths in the same fiber effectively increases the bandwidth capacity of a fiber and thus negates the immediate need to install additional fibers or increase the data bit rate to extremely high levels. That is, WDM enables transporting the equivalent bandwidth of several OC-192 (or OC-768) signals by carrying each signal on a different wavelength in the same fiber. In the full low-loss range of a single mode fiber (1200–1600 nm), some 1000 wavelength channels separated by 50 GHz may be used. At 40 Gb/s per wavelength, a total aggregate bandwidth of 40 Tb/s per fiber may be achieved. Assuming 50% utilization of a 432-fiber cable, the total aggregate bandwidth is an astonishing 8000 Tb/s.

United States Patent [19]

Robertson et al.

[11] **Patent Number: 4,776,655**

[45] **Date of Patent: Oct. 11, 1988**

[54] **SINGLE MODE OPTICAL WAVEGUIDES OF RECTANGULAR CROSS-SECTION**

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[73] Assignee: **British Telecommunications**, London, England

[21] Appl. No.: **904,280**

[22] Filed: **Sep. 8, 1986**

[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**[4] **G02B 6/10**

[52] **U.S. Cl.** **350/96.12**; 350/96.17

[58] **Field of Search** 350/96.12, 96.17, 96.15

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Primary Examiner—John Lee

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[57] **ABSTRACT**

An optical waveguide device, suitable for coupling to optical fibers, provides a combination of narrow optical confinement and small changes in refractive index along a first axis, with broad optical confinement and large changes in refractive index along a second, perpendicular axis. A rib waveguide in which a single transverse mode beam can propagate, comprises a thin guiding layer **2** sandwiched between a pair of relatively thick confining layers **1**, **3** of refractive index only slightly less than that of the guiding layer **2**. The rib is etched through both the upper confining layer **3** and the guiding layer **2** and is exposed at its sides and top to air.

9 Claims, 1 Drawing Sheet

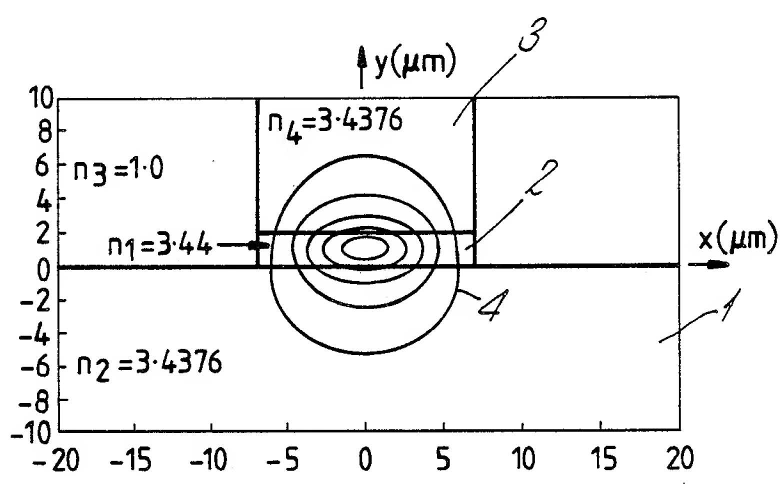


Fig.1.

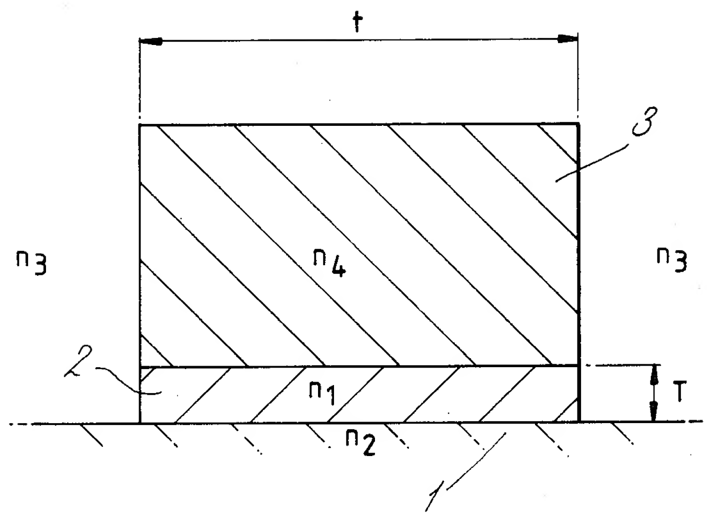
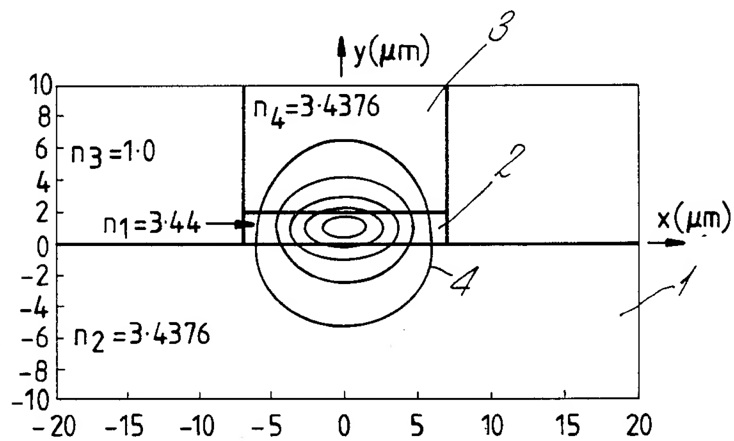

t
3
n_3
n_4
n_3
2
n_1
T
n_2
1

Fig.2.


y(μm)
3
n_4=3·4376
n_3=1·0
2
n_1=3·44
x(μm)
4
1
n_2=3·4376
10
8
6
4
2
0
-2
-4
-6
-8
-10
-20
-15
-10
-5
0
5
10
15
20

SINGLE MODE OPTICAL WAVEGUIDES OF RECTANGULAR CROSS-SECTION

The present invention relates to optical waveguide devices for use in optical communications systems.

Optical waveguides are used in optical communications both in waveguide devices, such as directional coupler switches, phase modulators and interferometric amplitude modulators, and in optical fibres.

An optical waveguide in general comprises a structure having a guiding zone, a confining zone or zones around the guiding zone, and a port for coupling electromagnetic radiation to the guiding zone. The guiding zone has a higher average refractive index than that of the confining zone or zones and, in use, radiation coupled at the port travels along the guiding zone.

It is preferable that signal losses are kept as low as possible in an optical communications system and it is important in the design of a waveguide device for use in such a system firstly that propagation losses within the device are low and secondly that coupling losses between it and adjacent components are low. Waveguide devices have been developed whose propagation losses are as low as 0.1 dB/cm but problems have arisen in achieving low coupling losses. In particular problems have arisen where a waveguide device is to be coupled to an optical fibre.

In order to achieve low coupling losses between two waveguides, the distribution of electromagnetic radiation at the ports of each should be roughly equivalent. It has proved extremely difficult however to manufacture waveguide devices in which the distribution of electromagnetic radiation is roughly equivalent to that of the optical fibres commonly in use today.

In an optical fibre the usual arrangement is that the guiding and confinement zones are produced by changes in refractive index which are distributed in a circularly symmetric or elliptical manner in the cross-section of the fibre. The majority of optical fibre now used in telecommunication systems, particularly in long distance systems, is monomode which has a core of higher refractive index of the order of 15μm or less wide, and a cladding of lower refractive index whose outer diameter is of the order of 125μm. These fibres are used to transmit radiation of wavelength in the range 0.8 to 1.65μm, the radiation propagating along the fibre in a single transverse mode. The beam spot generally has dimensions in the range 5 to 15μm and the cross-section of the beam is circularly symmetric or elliptical as a result of the distribution of refractive index changes in the fibre.

(It should be noted that where beam or beam spot dimensions are given in this specification, they refer to the full width to the 1/e points of the radiation distribution in the beam or beam spot.)

A waveguide device, unlike an optical fibre, is generally based on a slab of material in which changes in refractive index are more easily produced along flat interfaces than in curved distributions. For instance a semiconductor waveguide device may be manufactured in the form of epitaxially grown layers of material on a substrate. Changes in refractive index can then be produced in each of two perpendicular directions. Firstly, changes can be produced at the interfaces between the layers of material by using materials of different refractive indices. Secondly, changes in the perpendicular direction can be produced by making steps in the layers of material, for instance by etching using a mask. The steps may then either be left exposed to air, which has a low refractive index compared to semiconductor material, or buried in suitable material of preselected refractive index.

A simple form of waveguide device, a semiconductor rib waveguide, may comprise a substrate onto which are grown, epitaxially, three consecutive layers of material: two confining layers separated by a guiding layer, the refractive index of the guiding layer being greater than those of the confining layers. In a secondary role to that of producing a confinement zone, the lower confining layer prevents absorption of propagating radiation by the substrate and the upper confining layer prevents absorption by any metal contact layer which may be applied to the top of the device. Material is removed from at least part of the thickness of the upper confining layer, and may also be removed from at least part of the thickness of the guiding layer, to produce an upstanding rib. The guiding zone then comprises the guiding layer in the region of the rib and adjacent regions of the confining layers. Confinement is provided by the refractive index differences between the guiding layer and the confining layers and, perpendicularly to that, by the refractive index changes at the sides of the rib.

Suitable materials out of which such a semiconductor waveguide device may be constructed include the III-V semiconductor materials and may comprise gallium arsenide and gallium aluminium arsenide, or indium phosphide and indium gallium arsenide phosphide. In either of these cases differences in refractive index of the materials can be controlled by known methods such as by varying the proportions of gallium and aluminium present in the materials.

(It should be noted that throughout this specification terms such as "upper" and "lower" which might be taken to imply a particular orientation of an object are used for convenience of description only and should not be taken as a limitation.)

In alternative forms of the rib waveguide device, the rib may be buried in a subsequent growth step or the layers may each be a composite of thinner layers of different refractive indices. The confining layers do not necessarily have the same, or the same average, refractive index as each other.

Waveguide devices may alternatively be constructed out of dielectric materials such as lithium niobate. In this case, the guiding and confinement zones are produced by different techniques but again changes in refractive index occur along substantially flat planes in the device.

By varying the positions of the changes in refractive index, and by varying the values of those changes, the nature of the beam which will propagate in the device can be controlled. In the semiconductor rib waveguide described above, the dimensions of the rib, and the materials selected for the different layers, can be varied so as to control the beam.

In order to achieve a device in which a single transverse mode beam will propagate, it is known to use relatively narrow optical confinement: that is, the positions of changes in refractive index which act to confine radiation to the guiding zones are physically close to each other. This results in a single transverse mode but also a small spot size. It is here that problems arise in coupling the device to an optical fibre. Although it is relatively easy to achieve a beam of a suitably shaped cross-section, it is not easy to achieve it with a large

enough spot size for good coupling to the fibres in common use. To achieve a larger spot size it has been proposed to use relatively broad optical confinement, that is, to move the positions of the changes in refractive index further apart. However this moving of the positions may cause the transmission to become multimode. The single mode transmission can be retained by reducing the value of the changes in refractive index but this tends to require such small changes that the mass production of the device becomes impractical.

It is an object of the present invention to provide a single mode waveguide device for use in optical communications systems which can be designed to have a large spot size but is easier to manufacture than devices of the past.

According to a first aspect of the present invention, there is provided a single mode waveguide device, for coupling optical radiation to a single mode optical fibre, comprising a guiding zone determined in each of two perpendicular directions by a region of higher refractive index bounded on each side by regions of lower refractive index, wherein in a first of the directions the changes in refractive index are large and provide broad optical confinement, and in a second of the directions the changes in refractive index are small and provide narrow optical confinement, the regions of lower refractive index extending far enough away from the regions of higher refractive index that radiation propagating in the device in use does not leak significantly beyond the regions of lower refractive index, the arrangment being such that the beam spot of the waveguide device is at least substantially elliptical.

A large change in refractive index in this context may mean for instance of at least 0.02, and a small change in refractive index in this context may mean for instance in the range 0.0001 to 0.01 inclusive.

Broad optical confinement in this context may mean that the changes in refractive index are separated by a distance which lies in the range from $(0.8w_1-2)$ to $2.3w_1$ inclusive, w_1 being the average of the values for the width of the beam spot of the device in each of the two directions, while narrow optical confinement in this context may mean that the changes in refractive index are separated by a distance of not more than w_1. For coupling the device to an optical fibre, w_1 may typically be required to lie in the range from 5 to 15μm inclusive.

According to a second aspect of the present invention there is provided a single mode waveguide device, for coupling to an optical waveguide of substantially circular, or other elliptical, beam spot size W_o, comprising a guiding zone and a confining zone, the guiding zone being provided by first and second pairs of parallel planar interfaces, the planes in which the interfaces lie together defining a region of material of rectangular cross-section, the first pair of interfaces being provided by the faces of a primary layer of material of thickness T and refractive index n_1 sandwiched between upper and lower secondary layers of material of average refractive indices n_2 and n_4, and the second pair of interfaces being provided at least partially by the sides of a region of the upper secondary layer of width t positioned between two regions of material of refractive index n_3, wherein the following constraints apply:

(i) (n_1-n_3) is greater than or equal to 0.02;

(ii) (n_1-n_4) and (n_1-n_2) each lie in the range 0.01 to 0.0001 inclusive;

(iii) T is less than or equal to W_o;

(iv) t lies in the range to $(0.8W_o-2)$ to $2.3W_o$ inclusive; and

(v) the thickness of the secondary layers is large enough that radiation does not leak beyond those layers in use of the device;

all measurements being in μm.

It has been found, surprisingly, that waveguide devices according to the present invention, for coupling to optical fibres of spot sizes lying in the range 5 to 15μm inclusive, should produce a single transverse mode beam inspite of the fact that optical confinement by means of a very. small change in refractive index is only provided in one of two perpendicular directions instead of in both. Because this is so however, the waveguide devices are easier to manufacture since accurate control over differences in refractive index only has to be exercised regarding two interfaces instead of four as has been done in the past.

Further inspite of the apparently substantial erea asymmetry of the guiding zone, the design is such that the beam spot is roughly circularly symmetrical, or elliptical, matching that of an optical fibre.

The region of the upper secondary layer of width t positioned between two regions of material of refractive index n_3 may comprise an upstanding rib formed by opposing steps in the upper secondary layer to either side of which lies the material of refractive index n_3. Alternatively, the steps may extend past the upper secondary layer and into the primary layer, optionally extending as far as the lower secondary layer.

Waveguide devices according to the present invention can be manufactured for example out of semiconductor materials by standard production techniques such as metal organic vapour phase epitaxy (MOVPE) growth stages and etching steps.

A rib waveguide device according to an embodiment of the present invention will now be described, by way of example only, with reference to the accompanying figures in which:

FIG. **1** shows a cross-section of the device; and

FIG. **2** shows a contour plot of an electromagnetic radiation field distribution of such a device.

Referring to FIG. **1**, the rib waveguide device comprises a guiding layer **2** sandwiched between two confining or buffer layers **1**, **3**. The lower buffer layer **1**, only a part of which is shown, lies on a substrate (not shown) while the guiding layer **2** and upper buffer layer **3** provide the rib of the device.

The device is designed for use with optical fibres of beam spot size 10μm, transmitting radiation of wavelength λ equal to 1.55μm, distributed across the beam in a manner which is at least approximately Gaussian.

The lower buffer layer 1 is 12μm thick and consists of GaAlAs having a refractive index n_2 of 3.4376. The guiding layer **2** has a thickness T of 2μm and consists of Ga As aving a refractive index n_1 of 3.44. The upper buffer layer **3** is 8μm thick, again consists of GaAlAs and has a refractive index n_4 also of 3.4376. The rib has a width t of 14μm. To either side of the rib and above it lies air of refractive index n_3 equal to 1.0.

Referring to FIG. **2**, it has been shown that the device described above would produce a single mode beam whose electromagnetic field distribution can be represented by substantially circularly symmetric contour lines **4**.

Further, it has been calculated that a device as described above would give a coupling efficiency of 87°/o (0.6 dB) when coupled to a circularly symmetric optical

fibre with a spot size W_o of 10μm and a Gaussian field profile.

Although the rib waveguide described with reference to FIG. 1 has a rib exposed to air at its sides and top surface, in practice the rib may be buried. In the case that the rib is buried, the refractive index of the burying material will be represented by n_3.

The device described above is specific in that it is designed to operate with a fibre having certain characteristics including that of producing a circular beam spot of radiation of a particular wavelength, 1.55μm. However, in practice the waveguide device may be coupled to optical waveguides having any of a range of characteristics.

Where a waveguide device is intended to couple to a waveguide having an elliptical beam spot with a horizontal axial dimension of W_{ox} and a vertical axial dimension of W_{oy} (whose average is W_o), W_{ox} and W_{oy} falling within the criteria:

(a) $0.5 \leqq (W_{ox}W_{oy})W^2_o \leqq 2$; and

(b) $0.7 \leqq W_{ox}/W_{oy} \leqq 1.5$,

then using the notation:

n_1 = the refractive index of the primary layer,

n_2 = the refractive index of the lower secondary layer,

n_3 = the refractive index of the material to either side of the rib (in the above described embodiment this material being air)

n_4 = the refractive index of the upper secondary layer,

t = the width of the rib,

T = the thickness of the primary layer, and

λ = the wavelength of the radiation concerned, the design of the waveguide device may vary within the following design constraints without departing from the present invention:

(i) select T according to

$$2.388 \leqq W_{ox}/(W_{oy}-T/2) \leqq 1.194;$$

(ii) select n_1 and n_2 such that

$$\lambda/2\pi \leqq (n^2{}_1-n^2{}_2)^{0.5} \leqq \lambda/(\pi[T(W_{oy}-T)]^{0.5});$$

(iii) select n_3 such that

$$(n^2{}_1-n^2{}_3)^{0.5} \leqq 1.55\lambda/W_{ox};$$

(iv) select n_4 such that

$$\mathrm{Mod}[(n^2{}_2-n^2{}_4)/(n^2{}_1-n^2{}_2)] \leqq X; \text{ and}$$

$$\mathrm{Mod}[(n^2{}_2-n^2{}_4/(n^2{}_1-n^2{}_2)] \leqq Y;$$

where

$X=\tan^2(2\pi T[n^2{}_1-n^2{}_2]^{0.5}/\lambda)$; and

$Y=\tan^2([9.552T/W_{ox}]^{0.5})$; and

(v) select t such that

$$1.3155W_{ox}-\lambda/\pi(n^2{}_2-n^2{}_3)^{0.5} \leqq t; \text{ and}$$

$$t \leqq 1.3155W_{ox}-\lambda/\pi(n^2{}_1-n^2{}_3)^{0.5};$$

the thickness of the confining layers **1**, **3**, being great enough that radiation from the beam propagating in the waveguide device in use does not leak beyond the confining layers **1**, **3**. Regarding the latter, the confining layers, **1**, **3** may for instance be each at least equal to $2W_o/3$ in thickness.

It will be seen from the above that the refractive indices of the two confining layers **1**, **3** do not have to be equal.

A waveguide device falling within the above design constraints provides in essence a combination of narrow optical confinement with small differences in refractive index along one axis, and broad optical confinement with larger differences in refractive index along a perpendicular axis. Surprisingly, single transverse mode propagation is achieved in spite of the broad confinement and larger differences in refractive index along the perpendicular axis.

A waveguide device according to an embodiment of the present invention could be used as an end portion of a second device, such as a phase modulator, to couple it to an optical fibre. This would be advantageous where the second device required beam parameters which conflicted with those required for good coupling with an optical fibre.

It will be realised that the electromagnetic field distribution of a device is important in the region of the port to the guiding zone rather than along the length of the device since it is at the port that coupling with another optical component occurs.

Although reference has largely been made to coupling between waveguide devices and an optical fibre, it may be that coupling may be required to a component with beam characteristics similar to those of an optical fibre, the component itself not being an optical fibre. Waveguide devices according to embodiments of the present invention will also of course be appropriate for use with such components.

We claim:

1. A single mode waveguide device, for coupling optical radiation to a single mode optical fibre, comprising a guiding zone determined in each of two perpendicular directions by a region of higher refractive index bounded on each side by regions of lower refractive index, wherein in a first of the directions the changes in refractive index are large and provide broad optical confinement, and in a second of the directions the changes in refractive index are small and provide narrow optical confinement, the regions of lower refractive index extending far enough away from the regions of higher refractive index that radiation propagating in the device in use does not leak significantly beyond the regions of lower refractive index, the arrangement being such that the beam spot of the waveguide device is at least substantially elliptical.

2. A device according to claim **1** wherein the changes in refractive index in the first direction are greater than or equal to 0.02.

3. A device according to either one of claims **1** or **2** wherein the changes in refractive index in the second direction each lie in the range 0.0001 to 0.01 inclusive.

4. A device according claim **1** wherein the changes in refractive index in the first direction are separated by a distance which lies in the range from $(0.8w_1-2\mu m)$ to $2.3w_1$ inclusive, w_1 being the average of the values for the width of the beam spot of the device in each of the two directions in μm.

5. A device according to claim **1** wherein the changes in refractive index in the second direction are separated by a distance which is less than or equal to w_1, w_1 being the average of the values for the width of the beam spot of the device in each of the two directions.

6. A device according to either one of claims **4** or **5** wherein w_1 lies in the range from 5 to 15μm inclusive.

7. A single mode waveguide device, for coupling radiation of wavelength λ to a single mode optical waveguide having an elliptical beam spot of average dimension W_o along its two axes, comprising a guiding zone and a confining zone, wherein the guiding zone is provided by first and second pairs of substantially parallel planar interfaces, the planes in which the interfaces lie defining a region of material of rectangular cross-section, the first pair of interfaces being provided by the faces of a primary layer of material of thickness T and refractive index n_1 sandwiched between upper and lower secondary layers of material of average refractive indices n_2 and n_4, and the second pair of interfaces being provided at least partially by the sides of a region of the upper secondary layer of width t positioned between two regions of material of refractive index n_3, wherein the following design constraints apply:

(i) $(n_1-n_3)\geqq 0.02$;

(ii) (n_1-n_4) and (n_1-n_2) each lie in the range 0.01 to 0.0001 inclusive;

(iii) $T\leqq W_o$;

(iv) t lies in the range $(0.8W_o-2\mu m)$ to $2.3W_o$ inclusive; and

(v) the thickness of the secondary layers is such that radiation propagating in the device in use does not leak beyond them;

all measurements being made in μm.

8. A device according to claim 7 wherein the second pair of interfaces is partially provided by the sides of a region of the primary layer of width t positioned between two regions of the material of refractive index n_3.

9. A single mode optical waveguide of rectangular cross-section which is nevertheless especially suited for coupling optical radiation propagating therewithin to a single mode optical fibre having a generally circular distribution of radiation fields propagating therewithin, said waveguide comprising:

an optical radiation guide having an index of refraction n_1 and being of rectangular cross section with a thickness t and width w where $t<w$;

an upper buffer layer having an index of refraction n_4 where $n_4<n_1$;

a lower buffer layer having an index of refraction n_2 where $n_2<n_1$;

said upper and lower buffer layers being disposed along width w of respective opposite upper and lower sides of the guide so as to sandwich the guide therebetween and thereby provide narrow optical confinement across thickness t of the guide; and

a pair of side regions having an index of refraction n_3, where $n_3<<n_1$, said side regions bounding respective opposite lateral sides of said guide so as to sandwich the guide therebetween and to thereby provide broad optical confinement across the width w of the guide;

whereby radiation fields propagating along said waveguide are caused to have a generally circular distribution generally matching that expected in a single mode optical fibre.

* * * * *

United States Patent [19]

Dyott et al.

[11] **3,957,343**

[45] **May 18, 1976**

[54] **OPTICAL COMMUNICATIONS SYSTEMS**

[75] Inventors: **Richard Burnaby Dyott; John Leslie Stevenson,** both of London, England

[73] Assignee: **The Post Office,** London, England

[22] Filed: **Apr. 11, 1975**

[21] Appl. No.: **567,429**

Related U.S. Application Data

[63] Continuation of Ser. No. 417,052, Nov. 19, 1973, abandoned.

[30] **Foreign Application Priority Data**

Nov. 24, 1972 United Kingdom 54412/72

[52] **U.S. Cl.** .... **350/96 WG;** 350/96 C

[51] **Int. Cl.²** **G02B 5/14**

[58] **Field of Search** .... 350/96 WG, 96 C

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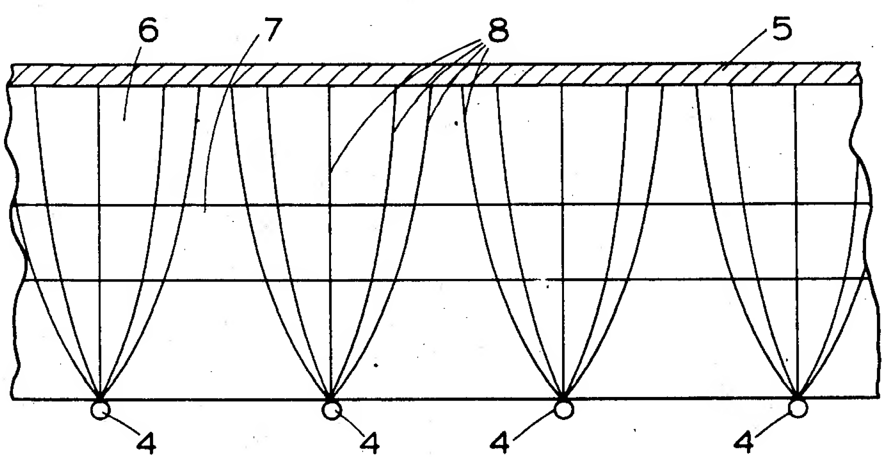
Primary Examiner—John K. Corbin
Assistant Examiner—Stewart Levy
Attorney, Agent, or Firm—Kemon, Palmer & Estabrook

[57] **ABSTRACT**

Energy propagating in a dielectric optical waveguide may be transferred from one mode of propagation to another by inducing a spatially undulatory variation in refractive index in the core of the dielectric optical waveguide. Such a variation may be induced by an electro-static field. The electro-static field may be directed either longitudinally of, or transversely of the dielectric optical waveguide. A suitably periodic electro-static field may be generated by positioning a suitable electrode structure about the dielectric optical waveguide. For certain applications it may be desirable to arrange for the spatial period of the electro-static field to vary in a random manner. By arranging for propagating modes to couple to non-propagating modes an optical modulator may be produced.

28 Claims, 4 Drawing Figures



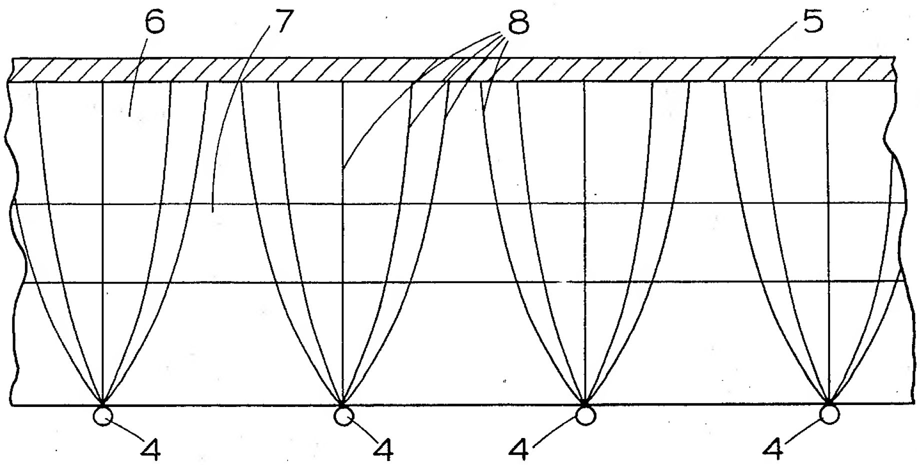


Fig.1

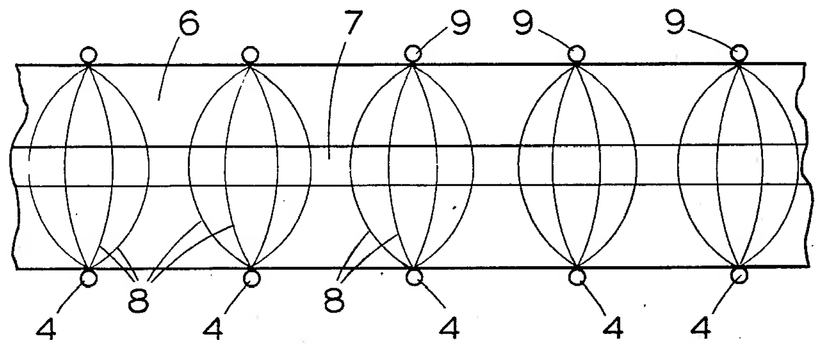


Fig.2

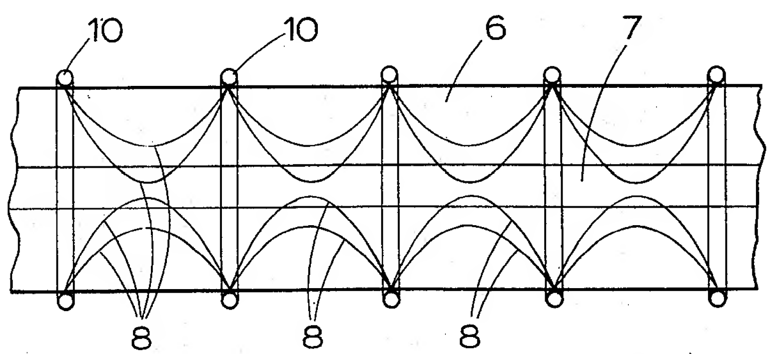


Fig.3

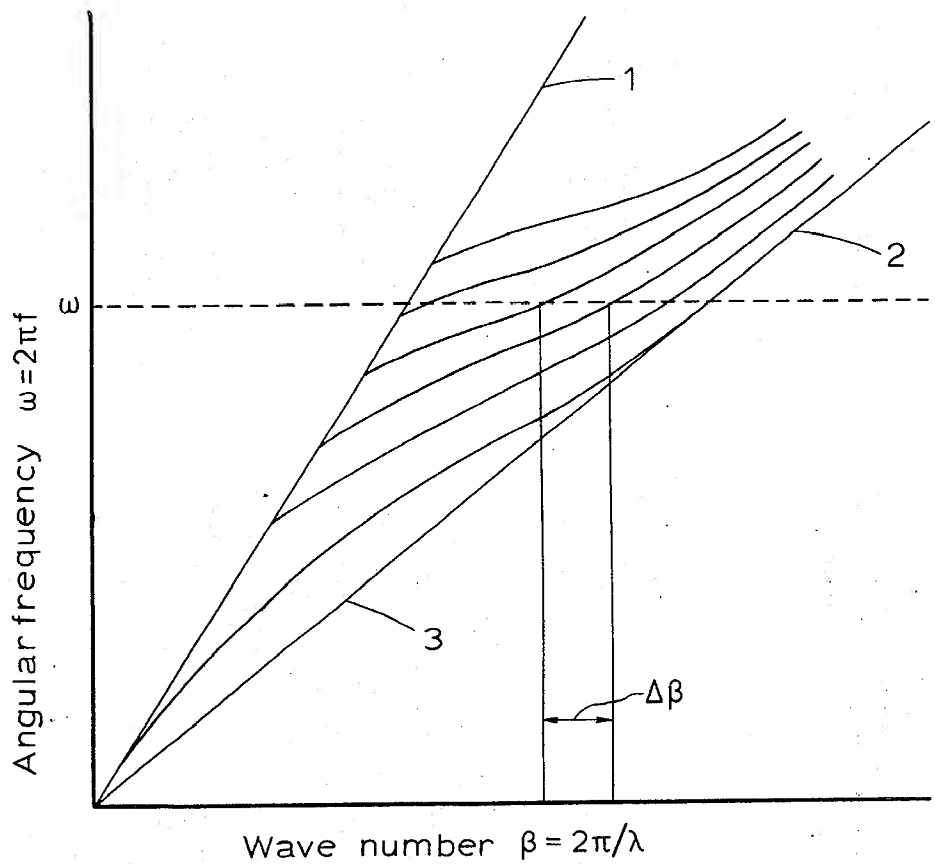


Fig.4

OPTICAL COMMUNICATIONS SYSTEMS

This is a continuation of application Ser. No. 417,052 filed Nov. 19, 1973, and now abandoned.

The present invention relates to a method of, and apparatus for, transferring energy between modes in a dielectric optical waveguide.

The terms "light" and "optical" as used in this specification are to be understood as referring to those regions of the electro-magnetic spectrum more usually designated as the infra-red, visible, and ultra-violet.

The term "mode" as used herein includes both propagating and non-propagating modes, a non-propagating mode being a mode in which the light is not guided by the dielectric optical waveguide, ie in which the light is radiated out of the guide.

One of the chief problems in the use of multi-mode dielectric optical waveguides for telecommunications, is the limit imposed on the information carrying capacity by group dispersion. Group dispersion is caused by the light propagating in different modes, having different velocities of propagation. This means that if, a train of pulses, say, is transmitted along a dielectric optical waveguide, the pulses become smeared out after travelling a certain distance because marks propagating in one mode have caught up with spaces propagating in another mode. This disadvantage can be avoided by the use of monomode fibres, however there are certain construction and cost problems associated with this solution to the problem, particularly if it is desired to use liquid cored dielectric optical waveguides.

Another approach to the problem is to ensure that light is not transmitted for any great distance in a single mode. In other words to transfer light energy between the modes so that, the mean velocity of transmission along the entire length of the waveguide is a constant. If this can be achieved the effects of group dispersion can be at least partially avoided.

Accordingly it is a first object of the invention to provide a method of, and apparatus for, transferring light propagating in a dielectric optical waveguide between modes so that the effects of group dispersion in smearing out intelligence carried by the light is at least partially eliminated.

The modes associated with a dielectric optical waveguide can be divided into two groups:

a. propagating modes, and

b. non-propagating modes.

Propagating modes are those in which the waveguide exerts a guiding action on the light, i.e., the light is physically confined to the guide. Non-propagating modes are modes in which the waveguide does not exert a guiding action, i.e., light in these modes is not physically bound to the waveguide. Thus if it is possible to construct a device for transferring light from one mode to another, the same device can act as a modulator by transferring light from a propagating mode to a non-propagating mode.

Accordingly it is a second or alternative object of the invention to provide a method of and apparatus for modulating light carried by a dielectric optical waveguide, by transferring light between a propagating and a non-propagating mode.

According to a first aspect of the invention there is provided a mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide having a core and a cladding comprising a section of dielectric optical waveguide having a core wherein refractive index varies as a function of position in a spatially undulatory manner, said variations of refractive index caused by a spatially undulatory electric field.

According to a second aspect of the invention there is provided a method of transferring energy between different modes of propagation in a dielectric optical waveguide having a core and a cladding wherein a spatially undulatory variation of refractive index is created in the core of the dielectric optical waveguide by a spatially undulatory variation in electric field.

According to a third aspect of the present invention there is provided a mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide, comprising a section of dielectric optical waveguide having a plate electrode disposed tangentially adjacent a surface of said section of dielectric optical waveguide, a plurality of strip electrodes disposed tangentially adjacent said surface of said section of dielectric optical waveguide in a serial array along said section of dielectric optical waveguide, each of said strip electrodes disposed axially transverse of said section of dielectric optical waveguide, said plurality of strip electrodes electrically isolated from said plate electrode.

According to a fourth aspect of the present invention there is provided a mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide, comprising a section of dielectric optical waveguide having a first group and a second group of strip electrodes disposed tangentially adjacent said surface of said section of dielectric optical waveguide in serial arrays along said section of dielectric optical waveguide, each of said strip electrodes disposed axially transverse of said section of dielectric optical waveguide, each strip electrode of said first group disposed diametrically opposite with respect to said dielectric optical waveguide a strip electrode of said second group, said first group of strip electrodes electrically isolated from said second group of strip electrodes.

According to a fifth aspect of the present invention there is provided a mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide comprises a section of dielectric optical waveguide having a plurality of ring electrodes arranged in a serial array axially of said section of dielectric optical waveguide, each ring electrode disposed circumjacent a surface of said section of dielectric optical waveguide.

An embodiment of the invention will now be described, by way of example, with reference to the accompanying drawings in which:

FIG. 1 shows a mode mixer in which an electric field axially transverse of the dielectric optical waveguide is used to generate spatially undulatory refractive index variations.

FIG. 2 shows a second embodiment of a mode mixer in which an electric field axially transverse of the dielectric optical waveguide is used to generate spatially undulatory refractive index variations.

FIG. 3 shows a mode mixer in which an electric field axially directed relative to the dielectric optical waveguide is used to generate spatially undulatory refractive index variations.

FIG. 4 whows a graph of angular-frequency against wave number for the different modes of propagation in

a dielectric optical waveguide.

If any sort of periodic structure is present in a dielectric optical waveguide, the light propagating in the waveguide will interact with the structure. This usually results in a mixing up of the modes propagated in the waveguide, i.e., transfer of energy from one mode to another or even the loss of light from the waveguide because of decoupling. A device for inducing a periodic structure in the waveguide is shown in FIG. **1**. In this case the periodic structure is an electrically induced periodic variation in refractive index. A dielectric optical waveguide of circular cross-section, having a core **7** and a cladding **6** is arranged between a plate electrode **5** and a serial array of strip electrodes **4**. The strip electrodes **4** are arranged axially transverse of the direction of propagation of light along the dielectric optical waveguide. The strip electrodes **4** are a wire grid across which the dielectric optical waveguide is laid. The dielectric optical waveguide has a core of nitrobenzene (liquid) and a cladding of soda-lime glass. The wire grid **4** is maintained at a high positive potential with respect to the plate electrode **5**. This has the effect of generating a spatially undulatory electric field **8** in the core of the dielectric optical waveguide. The electric field thus produced is substantially transverse to the direction of propagation of light in the dielectric optical waveguide. Since for all materials the refractive index is to a greater or lesser extent variable with applied electric field, a periodic variation of refractive index is induced in the core of the dielectric optical waveguide. Typically a dielectric optical waveguide used in this device may have a diameter of 100 microns, and the applied voltage may be 500 volts, so that if the electrodes are placed tangentially adjacent the dielectric optical waveguide, a field of the order of 5×10^6 volts/meters is induced.

The electrode system of FIG. **1** may be replaced by the electrode system shown in FIG. **2**. In this embodiment the plate electrode is replaced by a second serial array of strip electrodes **9**. Each strip electrode **9** is positioned diametrically opposite a strip electrode **4**. The field produced by two sets of strip electrodes is more nearly axially transverse of the dielectric optical waveguide than in the case where a single serial array of strip electrodes is used in conjunction with a plate electrode.

If the electrode configuration of FIG. **3** is used the spatially undulatory electric field produced is substantially parallel to the direction of propagation. In this embodiment a serial array of ring electrodes **10** is used. Adjacent electrodes are connected to potentials of opposite polarity so that the electric field **8**, is directed, in the core, in a direction substantially parallel to the direction of propagation. With this particular electrode configuration, a solid core of crystalline metanitroanaline may be used. The metanitroanaline, which crystallizes in an orthorhombic form (with a symmetry defined by the point group mm2) is arranged so that its c-axis is parallel to the direction of propagation in the dielectric optical waveguide. When metanitroanaline, is used as the core material, a cladding of lead flint glass, is employed so that the refractive index difference between core and cladding is not too great.

If the device is intended merely to couple two modes together the electric field and resultant refractive index variations should have a regular periodic structure. This is achieved by using equi-spaced electrodes in the serial arrays of electrodes. However if the device is to be used for mode mixing or as a modulator a regular period associated with the electric field may result in inadequate mixing or weak modulation unless the length of dielectric optical waveguide to which the spatially undulatory field is applied is excessive. This effect can be partially offset by varying the relative position of the electrodes, between certain limits, in a random manner, so that the resultant electric field has a pseudo-random structure. The cause of this effect will be discussed later.

The electrode systems for use with the mode mixers illustrated in FIGS. **1–3** may be formed on the dielectric optical waveguide by a photo-lithographic technique. The photo-resist may be exposed to a light pattern generated by a suitable mask, or alternatively interference fringe patterns may be generated using a suitable monochromatic light source, e.g., a laser. Under certain circumstances it may be advantageous to rotate the dielectric optical waveguide during exposure of the photo-resist.

The mode of actions of the mode couplers described above can be explained by an approximate theory. In FIG. **4**, angular frequency, $\omega=2\pi f$, is plotted against the wave number, $\beta=2\pi/\lambda$ to give a family of dispersion curves for the propagation of different modes of a dielectric optical waveguide. The two limiting lines **1** and **2** represent the velocity of light in the cladding and core respectively. Line **3** indicates the HE_{11} mode, which is the fundamental mode. In order to transfer energy from one mode to an adjacent mode it is necessary to shift the wave number by $\Delta\beta$. An approximate value for $\Delta\beta$ can be obtained in the following way. The extreme values of β for propagation in the core and cladding, β_1 and β_2 are given by

$$\beta_1 = \frac{2\pi n_1}{\lambda_o} \text{ and } \beta_2 = \frac{2\pi n_2}{\lambda_o} \qquad .1$$

where λ_0 is the free space wavelength of the light, n_1 is the core refractive index and n_2 is the cladding refractive index.

$$\text{Therefore, } \beta_1 - \beta_2 = \frac{2\pi}{\lambda_o}(n_1 - n_2) \qquad .2$$

Now the number of modes N carried by a multi-mode dielectric waveguide is:

$$N \simeq \frac{V^2}{2} \text{ where } V = \frac{2\pi\alpha}{\lambda_o}(n_1^2 - n_2^2)^{1/2} \qquad .3$$

where, α is the core radius

$$\text{Therefore, } N \simeq \tfrac{1}{2}\left(\frac{2\pi\alpha}{\lambda_o}\right)^2 (n_1^2 - n_2^2) \qquad .4$$

The difference in β, $\Delta\beta$ between the modes is approximately given by

$$\Delta\beta = \frac{\beta_1 - \beta_2}{N} = \frac{\left(\frac{2\pi}{\lambda_o}\right)(n_1 - n_2)}{\tfrac{1}{2}\left(\frac{2\pi\alpha}{\lambda_o}\right)^2 (n_1^2 - n_2^2)} \qquad .5$$

continued

$$\text{Therefore, } \Delta\beta = \frac{\lambda_o}{\pi a^2(n_1+n_2)}$$

If a periodicity is introduced into the waveguide such that

$$\Delta\beta = \frac{2\pi}{\lambda_p} \quad .6$$

where λp is the periodic pitch, it is to be expected that some sort of coupling between the modes will occur. Combining equations (5) and (6) gives

$$\lambda_p = \frac{2\pi^2 a^2}{\lambda_o}(n_1+n_2)$$

On the basis of the simple theory above it might be supposed that if λp has a value sufficient to ensure intermode coupling, then light would be progressively coupled through all the propagating modes and then into non-propagating modes. However in reality the last few propagating modes have a value of $\Delta\beta$ greater than that for the low order modes. Thus it is possible to choose $\Delta\beta$ so that some intermode coupling occurs but there is no coupling of light out of the waveguide.

The mode couplers described can be used, not only for intermode coupling, to reduce the group dispersion effect, but also as modulators. By varying the electric potential applied between the electrodes, the intensity of the light allowed to propagate in the waveguide is varied. The periodic pitch of the refractive index variations must of course be sufficiently small to ensure that light is coupled out of the waveguide. The device thus acts in a similar manner to a variable attenuator. There is of course no reason why the device when used as a modulator, should not be used with monomode dielectric optical waveguides.

Because $\Delta\beta$ is larger for the high order modes than for the low order modes, the simple theory discussed above cannot be used to calculate the value of $\Delta\beta$ to be used in a modulator. It can be shown by an approximate theory that the criterion for intercoupling the modes so that the highest order mode is coupled out of the core, is given by:

$$\frac{\Delta\beta}{\beta} \simeq \frac{\pi\delta}{V}$$

$$\text{where } \Delta\beta = \frac{2\pi}{\lambda_p};\ \beta = \frac{2\pi n_1}{\lambda_o};\ \delta = 1 - \left(\frac{n_2}{n_1}\right)^2$$

$$\text{and } V = \frac{2\pi a}{\lambda_o}(n_1^2-n_2^2)^{1/2}$$

A periodic variation of index of pitch λp thus calculated will eventually couple all modes out of the core into the radiation field. It seems experimentally, however, to be a slow process needing a long length of dielectric optical waveguide exposed to a spatially undulatory electric field. This may well be because a well-defined pitch will only couple strongly those modes whose propagation constants β_1 and β_2 differ by $\Delta\beta$. Although there is almost a continuum of modes and although it follows that all modes must eventually be coupled out, it may need some distance of fibre to accomplish this.

Two possible alternatives are:

a. vary the pitch **80** p in a random fashion about the mean value as calculated. This will spread the values of $\Delta\beta$ and hasten the mode coupling;

b. make $\Delta\beta$ large enough to couple the lowest order mode directly to the radiation field.

In which case:

$$\Delta\beta \geqslant \frac{2\pi}{\lambda_o}(n_1-n_2)$$

$$\lambda_p \leqslant \frac{\lambda_o}{n_1-n_2}$$

This last method is the most effective.

What we claim is:

1. A mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide having a core of homogeneous phase and a cladding comprising:

a section of dielectric optical waveguide of substantially circular cross-section having a core, said core being of a type whose refractive index varies in response to the presence of an electric field; and

electrodes disposed on an external surface of the said cladding for applying an electric field to said core, said field being characterized by undulatory variations spaced along a direction of propagation in said wave guide to produce undulatory variations in the refractive index of said core correspondingly spaced along said core in said direction.

2. A mode coupler as defined by claim **1** wherein said core of said section of dielectric optical waveguide is nitrobenzene.

3. A mode coupler as defined by claim **1** in which said electrodes for applying said field to said core includes first and second groups of electrodes disposed adjacent said section of dielectric optical waveguide, said first group being electrically isolated from said second group and means for applying a potential difference between said first and second groups.

4. A mode coupler as defined by claim **3** wherein said first group of electrodes comprising a regular array of strip electrodes transverse said direction of propagation and said second group of electrodes comprises a single plate electrode diametrically opposed to, and electrically isolated from, said first group of electrodes.

5. A mode coupler as defined by claim **3** wherein said first and second groups of electrodes comprises regular arrays of strip electrodes transverse to said direction or propagation, each strip electrode of said first group having a single strip electrode of said second group disposed diametrically opposite with respect to said section of dielectric optical waveguide.

6. A mode coupler as defined by claim **3** wherein said first group of electrodes comprises a pseudo-random array of strip electrodes transverse to said direction of propagation and said second group of electrodes comprises a simple plate electrode diametrically opposed to, and electrically isolated from, said first group of electrodes.

7. A mode coupler as defined by claim **1** wherein said spatially undulatory electric field has a pseudo-random structure.

8. A mode coupler as defined by claim **7** in which said electrodes for applying said field to said core in-

cludes first and second groups of electrodes disposed adjacent said section of dielectrical waveguide, said first group being electrically isolated from said second group and means for applying a potential difference between said first and second groups.

9. A mode coupler as defined by claim 8 wherein said first and second groups of electrodes comprises pseudo-random arrays of strip electrodes transverse said direction of propagation, each strip electrode of said first group having a single strip electrode of said second group disposed diametrically opposite with respect to said section of dielectric optical waveguide.

10. A mode coupler as defined by claim 1 wherein said electric field is parallel to said direction of said propagation.

11. A mode coupler as defined by claim 10 wherein said undulatory electric field has a regular periodic structure.

12. A mode coupler as defined by claim 11 in which said electrodes for applying said field to said core includes first and second groups of electrodes disposed adjacent said section of dielectric optical waveguide, said first group being electrically isolated from said second group and means for applying a potential difference between said first and second groups.

13. A mode coupler as defined by claim 12 wherein each electrode of said first group and second group comprises a ring electrode disposed coaxially with respect to said section of dielectric optical waveguide, said ring electrodes disposed in a regular serial array in a direction parallel to said direction of propagation such that electrodes of said first group alternate with electrodes of said second group.

14. A mode coupler as defined by claim 10 wherein said undulatory electric field has a pseudo-random periodic structure.

15. A mode coupler as defined by claim 14 in which said means for applying said field to said core includes first and second groups of electrodes disposed adjacent said section of dielectric optical waveguide, said first group being electrically isolated from said second group and means for applying a potential difference between said first and second groups.

16. A mode coupler as defined by claim 15 wherein each electrode of said first group and second group comprises a ring electrode disposed coaxially with respect to section of dielectric optical waveguide, said ring electrodes disposed in an irregular serial array in a direction parallel to said direction of propagation such that electrodes of said first group alternate with electrodes of said second group.

17. A mode coupler as defined by claim 16 wherein said core of said section of dielectric optical waveguide is nitrobenzene.

18. A mode coupler as defined by claim 17 wherein said core of said section of dielectric optical waveguide is meta-nitroanaline.

19. A mode coupler as defined by claim 18 wherein said meta-nitroanaline is crystaline with a c-axis parallel to said direction of propagation.

20. A mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide, comprising a section of dielectric optical waveguide having a core of homogeneous phase and a cladding having a plate electrode disposed tangentially adjacent a surface of said section of dielectric optical waveguide and externally of said cladding, a plurality of strip electrodes disposed tangentially adjacent said surface of said section of dielectric optical waveguide and externally of said cladding in a serial array along said section of dielectric optical waveguide, each of said strip electrodes disposed axially transverse of said section of dielectric optical waveguide and diametrically opposite said plate electrode, said plurality of strip electrodes electrically isolated from said plate electrode.

21. A mode coupler as defined in claim 20 wherein said plurality of strip electrodes are equispaced.

22. A mode coupler as claimed in claim 20 wherein each of said plurality of strip electrodes are separated from adjacent electrodes by distances which are randomly valued between predetermined limits.

23. A mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide comprising a section of dielectric optical waveguide having a core of homogeneous phase and a cladding a first group and a second group of strip electrodes disposed tangentially adjacent said surface of said section of dielectric optical waveguide and externally of said cladding in serial arrays along said section of dielectric optical waveguide, each of said strip electrodes disposed axially transverse of said section of dielectric optical waveguide, each strip electrode of said first group disposed diametrically opposite with respect to said dielectric optical waveguide, a strip electrode of said second group, and said first group of strip electrodes electrically isolated from said second group of strip electrodes.

24. A mode coupler as claimed in claim 23 wherein the strip electrodes of said first group are equi-spaced and the strip electrodes of said first group are equi-spaced.

25. A mode coupler as claimed in claim 23 wherein each of the electrodes of said first group are separated from adjacent electrodes by distances which are randomly valued between predetermined limits, and each of the strip electrodes of said second group are separated from adjacent electrodes by distances which are randomly valued between predetermined limits.

26. A mode coupler for transferring energy between different modes of propagation in a dielectric optical waveguide comprising a section of dielectric optical waveguide having a core of homogeneous phase, a plurality of ring electrodes arranged in a serial array axially of said section of dielectric optical waveguide, each ring electrode disposed circumjacent a surface of said section of dielectric optical waveguide and externally of said cladding.

27. A mode coupler as claimed in claim 26 wherein said ring electrodes are equi-spaced.

28. A mode coupler as claimed in claim 26 wherein said ring electrodes are separated from adjacent electrodes by distances which are randomly valued between predetermined limits.

* * * * *

United States Patent [19]

Boudreau et al.

[11] **Patent Number: 5,011,247**

[45] **Date of Patent: Apr. 30, 1991**

[54] **UPTAPERED SINGLE-MODE OPTICAL FIBER PACKAGE FOR OPTOLECTRONIC COMPONENTS**

[75] Inventors: **Robert A. Boudreau**, Hampton, N.H.; **William C. Rideout**, Townsend, Mass.

[73] Assignee: **GTE Laboratories Incorporated**, Waltham, Mass.

[21] Appl. No.: **487,497**

[22] Filed: **Mar. 2, 1990**

[51] **Int. Cl.**[5] **G02B 6/42**

[52] **U.S. Cl.** **350/96.2**; 350/96.18

[58] **Field of Search** 350/96.15, 96.18, 96.2; 357/74, 17, 19, 80, 81

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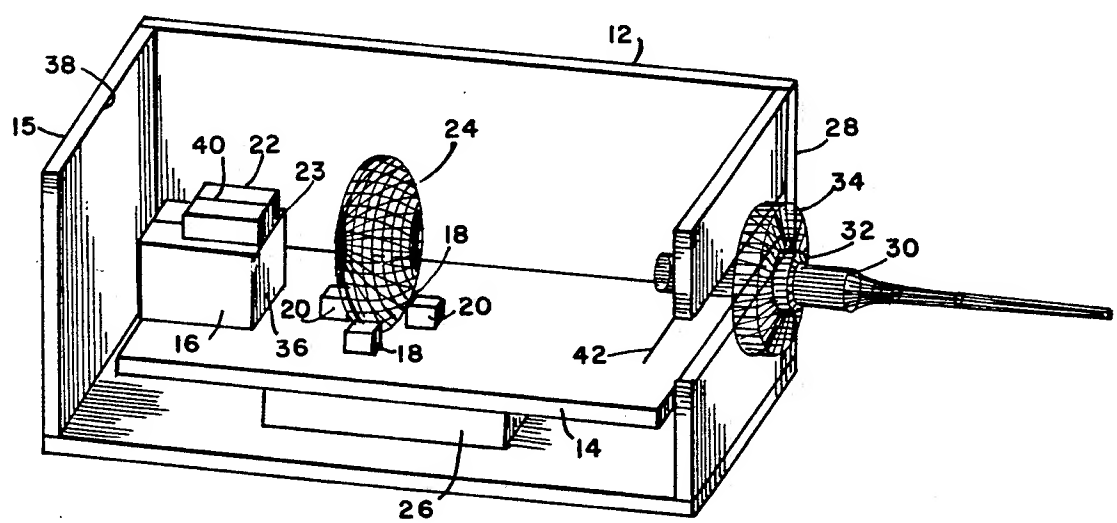
Primary Examiner—John D. Lee
Assistant Examiner—John Ngo
Attorney, Agent, or Firm—Victor F. Lohmann, III; James J. Cannon, Jr.

[57] **ABSTRACT**

A package for an optoelectronic device, such as a laser, having a photo-active element optically coupled to an uptapered single-mode optical fiber which connects said optoelectronic array to an external device includes a housing having a solderable substrate to which the device is secured, a graded index lens also secured to said substrate at a distance calculated to provide a known magnification of light beam emanating from said laser and an uptapered single-mode optical fiber mechanically positioned and actively aligned to said mangified light beam to achieve optimal optical coupling to said optoelectronic device. The package includes a plurality of reference marks and surfaces such that the laser, the lens and the uptapered end of a single-mode optical fiber may be positioned for precise optical coupling using an active alignment for final adjustments. The reference surfaces include a pedestal for the laser and a plurality of stops for the lens integrally formed with the substrate. The package also includes a fiber tube and flange for mechanically positioning the uptapered fiber. The precisely calculated spacing based on the spacing of said photo-active element, the magnification of said lens, and the fiber positioning is achieved by mechanical means.

26 Claims, 4 Drawing Sheets



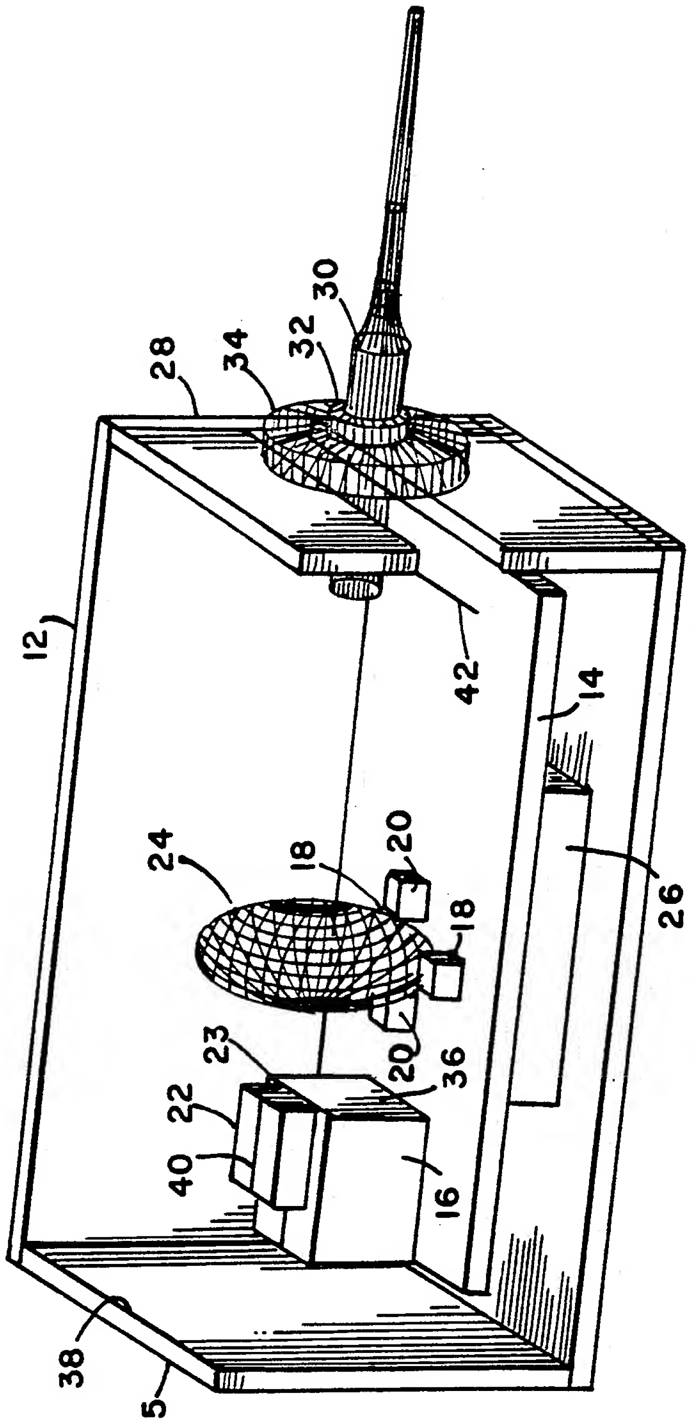


FIG.1

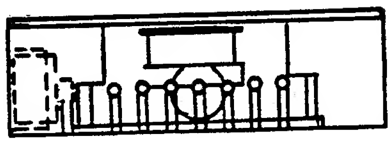


FIG.2C

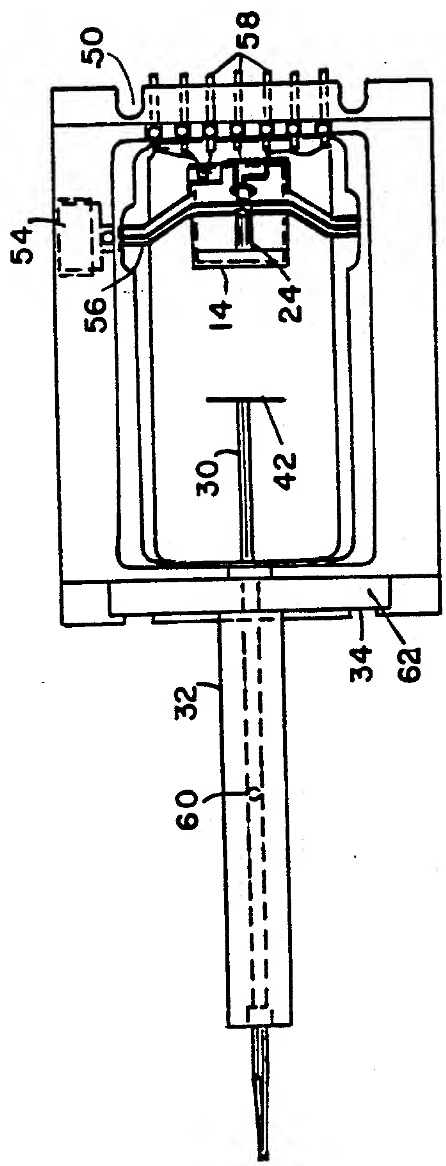


FIG. 2A

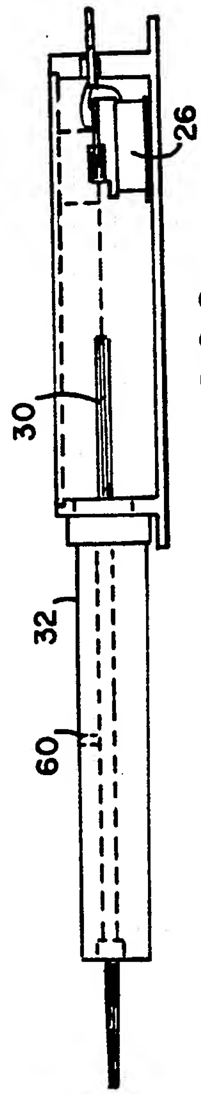


FIG.2B

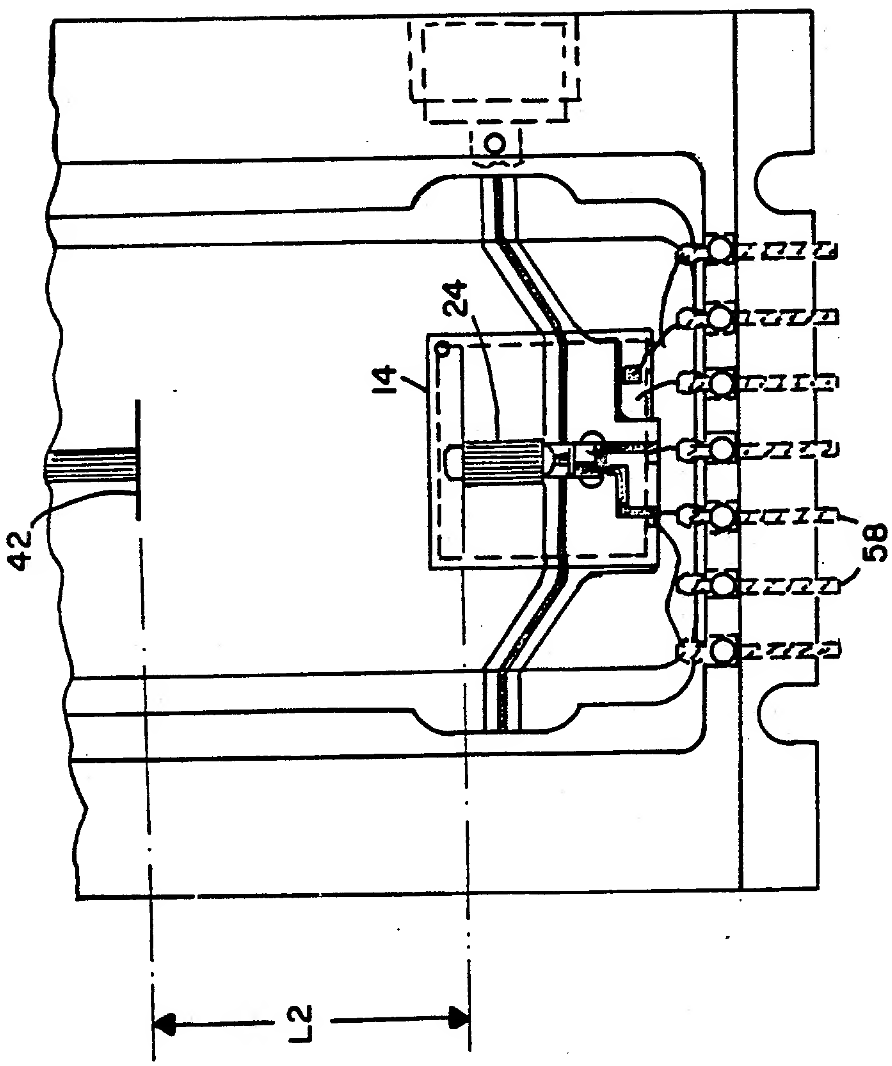


FIG.3

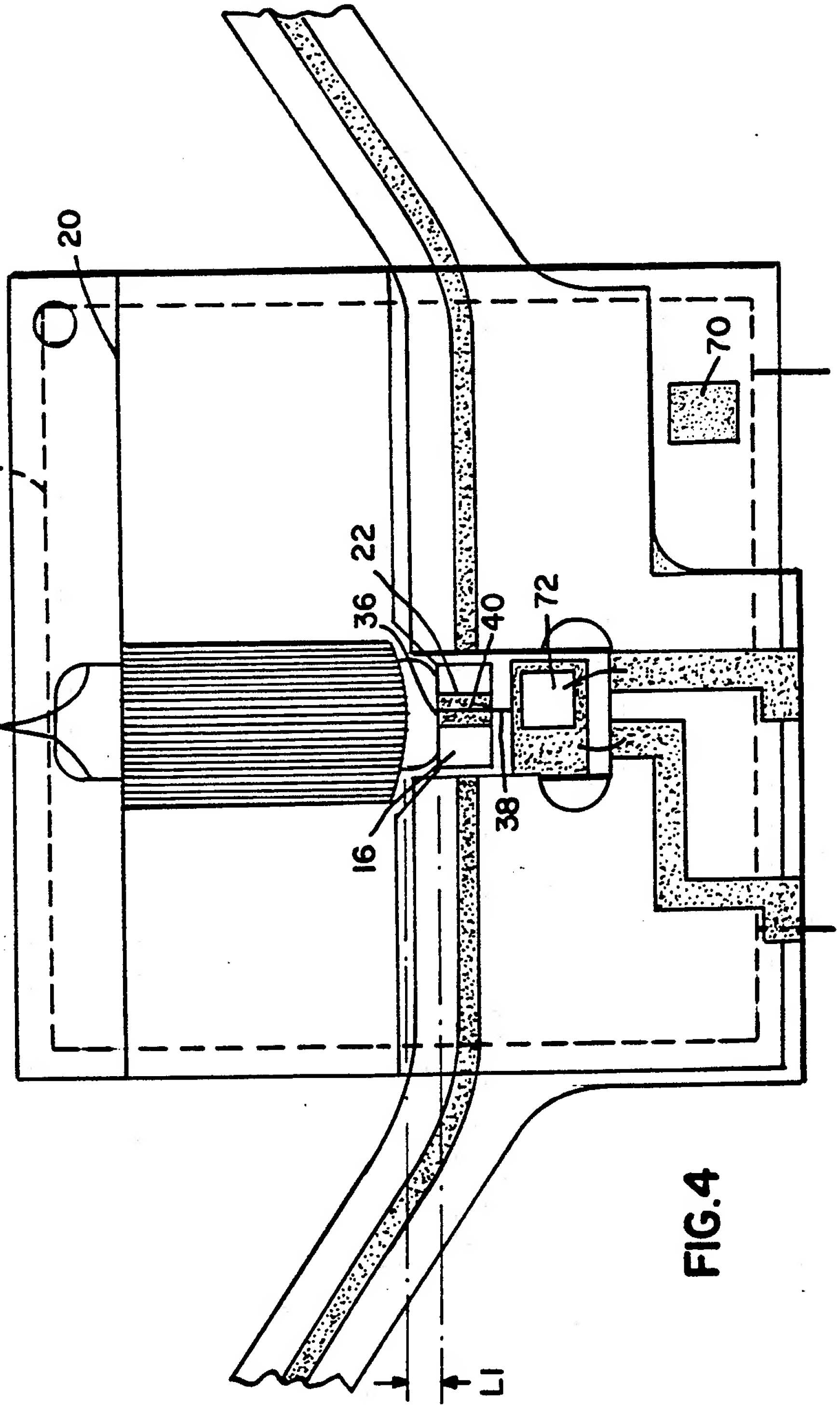


FIG.4

UPTAPERED SINGLE-MODE OPTICAL FIBER PACKAGE FOR OPTOLECTRONIC COMPONENTS

BACKGROUND OF THE INVENTION

This invention relates to packaging of optoelectronic components which generate or process signals that pass through optical fibers. In particular, it addresses the critical need for providing stable, low-cost alignment of single-mode optical fibers to a single packaged device, such as a semiconductor laser.

An optoelectronic package is a container or housing that provides protection and support for both active and passive components contained within it. These components and their interconnection represent an optical-electrical circuit and define the function of the package. The package also includes a means of connecting the internal components with the external environment, usually as electrical feed-through and optical fiber. Our invention is concerned with the optical fiber and how it is connected to the components within the package.

To make an optical connection between an optical fiber and an optoelectronic component within a package, it is necessary to position or align the optical fiber in a way that allows efficient coupling between the optical fiber and the optoelectronic component. The precision needed for the alignment depends on the size of the light-emitting or light receiving elements, the type of optical fiber, and any type of focusing or defocusing elements which may be present. Optical fiber transmits light through its inner core, which is much smaller than the diameter of the optical fiber. There are two classes of optical fiber presently used in packaging semiconductor devices: single-mode and multi-mode, with typical core diameters of about 10 microns and 50 microns, respectively. Many telecommunication applications use single-mode optical fiber because of the superior bandwidth arising from its reduction of mode partition noise.

The prior art for packaging semiconductor lasers is predominantly concerned with the easy task of aligning large cored multi-mode optical fiber. Multi-mode optical fiber is of little value for telecommunications because it suffers from mode-partition noise when used for high speed transmissions over a distance.

Laser packaging with single-mode optical fiber has been done with optical fibers which have their ends either cleaved or tapered and lensed. A cleaved optical fiber has an optically flat end, while a tapered and lensed optical fiber is drawn down to a point in a fashion that aids light entering the fiber. Packages incorporating cleaved optical fibers require a separate lens, as does the package of this invention, while packages incorporating lensed optical fibers do not.

Packages utilizing cleaved or tapered and lensed optical fibers suffer from stability problems associated with lateral movement of the optical fiber with respect to the laser. For this reason, the alignment of the optical fiber with the laser for such packages is usually done with expensive piezo-crystal micromanipulators having submicron sensitivity. The optical fiber is fastened with expensive laser welding techniques or special solders.

As explained by Rideout, et al, "Improved LED and laser packaging using up-tapered single mode fibers," CLEO '89, Baltimore, Md., Apr. 25, 1989, the improved lateral tolerances arise from first magnifying the emitting spot image of the laser. The larger spot is then projected congruently onto the corresponding uptapered optical fiber. The lateral and angular sensitivities are:

$$\text{Lateral coupling} = \exp\frac{-x^2}{w_o^2}$$

$$\text{Angular decoupling} = \exp\frac{-\pi^2 w_o^2/\theta^2}{\lambda^2}$$

where the symbols mean:

W_o=spot radius of the optical fiber;
λ=wavelength
θ=angular misalignment
x=lateral misalignment

The equations show that the spot radius of the light beam in the optical fiber determines these sensitivities. Since the spot radius is in the denominator of the lateral decoupling expression above, the benefit of decreased lateral sensitivity occurs with increased spot size. Conversely, the angular sensitivity becomes more detrimental since the spot radius is in the numerator of the angular misalignment expression above.

When performing optical fiber alignments, the lateral alignment is more difficult to achieve than the angular alignment. Thus, the net effect of using a lens to magnify the spot radius of the light beam for coupling it to a larger diameter uptapered optical fiber is beneficial.

It is worth noting that even though the thick section of the uptapered optical fiber does not qualify as a single-mode optical fiber diameter, it is short enough in length that it maintains only the single-mode. Thus, it is possible to obtain the advantage of the ease of alignment of a thick multi-mode optical fiber, while not losing the data transmission advantage of a thin single-mode optical fiber.

SUMMARY OF THE INVENTION

The principle object of the present invention is to provide an optoelectronic component package in which a single-mode optical fiber is easily and efficiently optically coupled to an active semicondutor laser.

A second object of the present invention is to provide such a package for an optical connection that permits long distance, high speed transmissions of telecommunications data and information for the semicondutor element.

Still a further object of the present invention is to provide such a package having a predictable, reproducible location of the optical fibers for maximum coupling efficiency, allowing for assembly line mass production of packaged optoelectronic components, since manufacturing is simplified, thereby reducing the costs of such packages.

In one aspect of the invention, a package for an optoelectronic device having an active element optically coupled to a single-mode optical fiber connecting said optoelectronic device to an external device includes a housing to enclose the necessary components to convert electrical signals to optical signals. A substrate carrier within said housing has a solderable surface and a plurality of reference means for precise positioning of elements within said package. An optoelectronic semiconductor laser device having an active element is positioned with respect to one of said reference means and secured to said carrier substrate. A graded index lens, having a numerical aperature sufficient to access opti-

cally said active element and having a curvature on one end closest to said optoelectronic device, is positioned with reference to a second of said reference means and secured to said substrate a fixed distance from said optoelectronic active element to yield a desired magnification of light beams emanating from said active element. An uptapered single-mode optical fiber extends from a third one of said reference means within said housing to the exterior of said housing through a port thereof, said optical fibers being precisely positioned by a fiber tube flange secured to a side wall adjacent said port of said housing, the uptapered end of said optical fiber being mechanically aligned, with respect to the third of said reference means, for optical coupling through said lens to said photo-active spot of said optoelectronic device, while the opposite end of said single-mode optical fiber is outside said housing.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic perspective view of a generalized embodiment of an optoelectronic package which illustrates a package according to the principles of the invention and the method of packaging an optoelectronic component according to the invention using reference marks to mechanically align an uptapered optical fiber to a semiconductor laser;

FIGS. *2a*, *2b* and *2c* are, respectively, top, side and end views of the preferred embodiment of an optoelectronic package, according to the invention;

FIG. **3** is a partially cut-away top view of the embodiment of an optoelectronic package of FIG. *2a*, enlarged to show details of the package; and

FIG. **4** is a top view of the embodiment of FIG. *2a*, further enlarged to show details of substrate carrier.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention pertains to packages for optoelectronic devices which provide stable alignment, using a mechanical method for quick and efficient optical coupling of an uptapered single-mode optical fiber to the photo-active spot of the semi-conductor element. The package controls the uptapered fiber optical tolerances, allowing a relaxation of the optical fiber positional tolerance.

The package of this invention uses a lens, with a sufficient numerical aperature and magnification, in conjunction with uptapered single-mode optical fiber. The alignment technique takes advantage of the relaxed mechanical tolerance and the magnification provided by the lens and the larger cored uptapered fiber optics. Such optical connections then permit independent transfer of telecommunications data and information for the semiconductor element.

Specifically, this invention provides a new package for optically coupling an uptapered single-mode optical fiber to a single packaged optoelectronic device using a single lens mechanically aligned with the semiconductor element in order to magnify the spot image of the photo-active element to expand the size of the emitted light beam. This image is then coupled to an uptapered optical fiber. This magnification greatly facilitates mechanical alignment and coupling of the semiconductor laser to the associated optical fiber by relaxing mechanical tolerances associated with the position of the ray of light coming from the laser.

Uptapered optical fibers are used because the effect of magnification increases the size of the beams or spot. These beams are best collected on the thick end of the uptapered fiber, where the size of the optical fiber best matches the size of the beams. For example, a typical uptapered optical fiber may have a core that is ten times larger on its thick end than the single-mode optical fiber that it tapers down to. This optical fiber is used with a lens that magnifies the spot size of the beam tenfold. This effect facilitates the alignment when assembling an optoelectronic package.

Mechanical alignment is also possible with these packages because the location of the semiconductor beam can be known with high precision relative to the package. This is because the semiconductor photoactive element is usually patterned on the semiconductor with photolithography to a high level of precision, about one micron, and the lens projects a precise image of this pattern towards the fiber. If a lens with known magnification is first positioned rigidly in a specified location, then the location of the projected beam is know. Alignment to this beam automatically aligns the uptapered optical fiber held in a fixture engineered with the geometry set by the known magnification determined by the lens.

FIG. **1** illustrates a generalized package for an optoelectronic component and a method for assembling the package, according to this invention. Package **10**, shown partially cutaway in FIG. **1**, comprises a housing **12**, which completely encloses the necessary components that convert input electrical signals to optical signals. Preferably, housing **12** is made of brass and has a removable top for access to the interior. A carrier **14** having a surface that is readily solderable, such as gold-plated copper or brass, is used to support the components. A pedestal **16** is secured to a first major surface of carrier **14** adjacent to a first end wall **15** of housing **12**, for mounting and positioning a semiconductor laser **22** having a photo-active spot **23**. Two lateral stops **18** and two axial stops **20** are also secured in a central location to the same major surface of carrier **14** for positioning a lens **24**, which is hard soldered prior to the optical fiber alignment. Preferably carrier **14**, pedestal **16** and stops **18**, **20** are integrally formed as a one-piece element. A thermoelectric cooler **26** is secured to the second major surface of carrier **14**. A second end wall **28** has a circular opening (not shown in FIG. **1**) to permit the insertion of the thick end of uptapered optical fiber **30**, which is enclosed in a fiber tube **32** and rigidly held perpendicular to end wall **28** by a large flange **34**. The lens **24** focuses the light from the photoactive spot **23** of laser **22** onto uptapered optical fiber **30**.

A plurality of mechanical features, and registration features and/or reference marks are incorporated into housing **12** and carrier **14** so that the total package **10** mechanically controls the uptapered-fiber optical tolerances, thus allowing a relaxation of the uptapered optical fiber positional tolerance. The uptapered-fiber optical tolerances controlled by package **10** are, the semiconductor position, the lens-to-semiconductor distance; the stability of lens attachment; and the tight angular control of the uptapered fiber.

A one-piece carrier **14** holds the laser **22** and the lens **24**. This controls the stability of the lens-to-semiconductor positional tolerance. Semiconductor **22** and lens **24** move in unison, despite shifts in other package parts caused by vibrations or thermal variations. The lens **24** is hard soldered prior to doing the optical fiber alignment to provide mechanical stability. For this optical element, lens **24**, stability is more important than exact

positioning. Some misalignment of the lens **24** can be compensated for during alignment of the uptapered optical fiber **30**.

The height of pedestal **16** controls the height of laser **22** (y-axis). The forward edge **36** of pedestal **16** serves as the forward reference mark for laser **22** (z-axis). A lateral reference mark **38** on pedestal **16** is aligned with an active region reference mark **40** on laser **22** (x-axis) to control the lateral position of laser **22**. Axial stops **20** control the lens-to-semiconductor distance, while lateral stops **18** control the horizontal alignment of the lens **24** to the photo-active spot **23** of laser **22**. The relative positioning of the laser **22** and the lens **24** is usually set to a positional accuracy of about one-half mil. This can be done off-line under a stereomicroscope, making use of the reference marks **36, 38, 40**.

The position of the lens **24** sets the magnification of the light-emitting area (photo-active spot **23**) of laser **22**. The magnification is set to best match the projected emitting area size with the core of the uptapered optical fiber **30**. The proper magnification position is set by the axial and lateral stops **18, 20**, which are registration features on the carrier **14**.

The uptapered optical fiber **30**, protected by a fiber tube holder **32**, is mounted and aligned externally to the package **10**. The uptapered end of optical fiber **30** extends inside the package to a fiber tip reference mark **42** on carrier **14**, which is a known distance from axial lens stops **20**. The package cover (not shown in the figures) is in place, so that the interior of the package is protected from damage. After fiber positioning, using reference marks **42, 20** the uptapered optical fiber **30** is actively aligned, requiring only crude low cost micrometers and is secured in position with simple means such as epoxy or screws (not shown in FIG. **1**). Active alignment means the fiber is aligned to maximize the light beam entering the fiber while the laser is operating. The uptapered optical fiber **30** and the fiber tube holder **32** are easily removed and replaced for packages that have suffered fiber damage, because interior parts need not be disturbed. The uptapered optical fiber is held perpendicular to the package by a large fiber flange **34** on the fiber tube holder **32**. This controls the angular uptapered optical fiber optical tolerance. It also improves stability because an uptapered optical fiber is more sensitive to angular misalignment than a conventional tapered and lensed or cleaved fiber.

A long focal distance between the lens **24** and the uptapered end of optical fiber **30** allows space to introduce optical elements such as filters and opto-isolators. In this space the light beam is nearly collimated, greatly simplifying the optical designs incorporating these elements.

The carrier **14** supporting the lens **24** and semiconductor **22** could be part of a circuit board, multi-chip module, or semiconductor waferboard carrying other optical and electronic components.

The lens **24** could be either a GRIN type, convex, plano-convex, or combination of several lenses. The only requirement is that it provide the necessary magnification to match light spot sizes with the uptapered end of optical fiber **30**.

Internal optical elements, such as opto-isolators or filters, can be located in the space between the lens **24** and the fiber **30** in any combination. Optical coatings could also be placed on the lens **24** to provide some of the function of these optical elements.

The registration or reference marks **18, 20, 36, 38, 42** on the carrier can be either mechanical stops, slots, pins, visual lines, steps or the like. The only requirement is that they be part of the carrier **14** and provide half mil or better accuracy for the lens **24** and the semiconductor **22** positions.

FIG. **1** shows the uptapered-fiber laser package with the lid removed so that the components are visible. This package incorporates an externally aligned uptapered fiber **30**, which is aligned and epoxied onto the outside of the package housing **12** at room temperature. This is the only active alignment, and can be performed without piezoelectric staging because of the relaxed lateral alignment tolerances. An AR-coated GRIN lens images the laser spot onto the uptapered fiber. This lens is soldered in place with high temperature solder for maximum stability.

FIGS. **2***a*, **2***b*, **2***c*, **3** and **4** illustrate details of the preferred embodiment of the uptapered single-mode optical fiber package according to the invention, as built and tested by the inventors. In these figures, the same reference numbers are used for corresponding parts as were used in FIG. **1**. Some elements not part of the invention are shown in the figures and mentioned in the specification without further elaboration.

FIGS. **2***a*, **2***b* and **2***c* are top, side and end views of the preferred embodiment of package **10**, illustrating its assembly. The following items are specific to this embodiment. A graduated index (GRIN) lens is used for lens **24**. A thermo-electric temperature control (TEC) **26** is present. This package is designed for epi-down semiconductor mounting. The carrier **14** does not extend the full length of the housing **12**, so the fiber tip reference mark **42** is on the base of the housing. A precision fiber tube **32** having an epoxy fill tube **60** for securing the optical fiber **30** after alignment holds the uptapered end of the optical fiber. Fiber tube flange **34** surrounding fiber tube **32** is fastened with epoxy to the outside of the at epoxy joint **62** to complete the alignment.

A screw mounting slot **50** is present. An SMA connector socket **54**, a high frequency microline **56** connected thereto, and seven d.c. in-line pin outs to provide high speed electrical signals complete the package. The package housing **12**, the fiber tube **32**, and the cover (not shown) are preferably, made of brass. Carrier **14** is preferably made of nickel and gold-plated copper. Package **10** in this embodiment is a high speed laser package having the uptapered fiber optical tolerance controls built into the package.

The lasers used in this package are 1.3 μm Vapor-Phase-Regrowth Burled Heterostructure (VPR-BH) lasers which have a demonstrated maximum bandwidth of 22 GHz and typical bandwidths of 15 GHz. Previously developed microstrip techniques are used to preserve the high frequency integrity of the package to 25 GHz.[5] Measurements of the variation in output power with slight changes in axial position of the uptapered indicate that back reflections which might introduce noise are less than −45 dB.

Excellent packaged coupling efficiencies of approximately 30% are obtained, which compare favorably to the maximum of 35% obtained on the laboratory bench, and 22% which are obtained using standard tapered-and-lensed fibers with a 12 μm radius tip and a 30° included angle.

The lens **24** used is a SELFOC GRIN lens (model PCH 1.8–0.22). The uptapered fiber **30** used was made

at GTE Laboratories Incorporated. It has an uptapered core size of 90μ and a single mode fiber core size 9μ. The fiber has a cut and polished tip to reduce light scattering loss.

The features of the package that control the uptapered-fiber optical tolerances are shown in Table I. Based on measurements of the package, the mechanical optical tolerances are shown in Table I. The use of a one piece carrier **14** eliminates tolerance "stack-up" arising if separate pedestal, lateral, and axial stops were bonded to the carrier.

TABLE I

Package Optical Control Tolerances	
Control Point	Tolerance
fiber tip reference	5.0 mils
fiber tube flange	0.5° of arc
axial stops	0.5 mils
lateral stops	0.5 mils
pedestal height	0.5 mils
active region reference	0.1 mils*
lateral reference	0.5 mils
forward reference mark	0.5 mils

*this item is normally defined with photolithography

This embodiment uses epi-down lasers. This eliminates the positional tolerance associated with the thickness of the wafer because the light emitting area is essentially at the pedestal/semiconductor interface. A reference mark **40** on the laser **22** enables its correct positioning on the pedestal **16** during assembly since the active region **23** in the semiconductor **22** is on the reverse side and not visible.

The GRIN lens **24** straddles a slot that determines its height above the carrier and its lateral position. The back edge of the lens registers with a raised edge on the carrier **14** that defines the axial stop **20**.

Table I compares observed tolerances for the uptapered fiber package with those of a typical lensed-and-tapered fiber package. These tolerances represent the measured misalignment which reduces the coupled power by about 25%.[2] The most important implications of this table for package design are: (1) the relaxed tolerance in the uptapered fiber position (lateral and transverse) is responsible for the increased yield, stability, and ease of assembly, (2) Critical tolerances (angular alignment and magnification) are met by built-in alignment marks and stops in the one-piece carrier, fiber flange, and housing, as schematically shown in FIG. **1**. The fiber flange was designed to automatically align the uptapered fiber parallel to the beam within 0.5°.

TABLE I

Tolerances for Components Within Package		
Approximate Tolerances	Uptapered Fiber Package	Tapered and Lensed Fiber Package
Fiber position:		
axial (parallel to fiber)	125 μm*	4 μm
lateral (|| to laser)	25 μm	0.5 μm
transverse (⊥ to laser)	25 μm	0.5 μm
Fiber angle	0.5°	12°
GRIN lens	13 μm	Not Applicable
Semiconductor laser	13 μm	Not Applicable

*component held to within tolerance by self-alignment to package hardware.

FIGS. **3** and **4** are enlarged top views of the embodiment of FIG. *2a*, showing further details of the package features which mechanically control the fiber optic tolerances. Referring now to these figures, two optical path distances, L1 (FIG. **4**) and L2, (FIG. **3**) should be maintained to achieve the correct magnification in the package **10**. **L1** is the distance between laser **22** and lens **24** while L2 is the distance between lens **24** and uptapered-fiber **50**. Distance **L1** was 15.5 mils. A magnification of 10 was used to optically match the semiconductor spot size 23 with the uptapered core. Distance **L1** can be checked with a low power (30×) stereomicroscope. Distance **L2** is controlled by setting the fiber tip at the fiber tip reference mark. **L2** is 0.475 inches.

For stability, the GRIN lens **24** is soldered to the carrier **16** with a reasonably hard 52/48 In/Sn 118° C. solder. The solder should be reflowed, and the lens position adjusted along its slot if **L1** is found incorrect when checked.

Following active alignment, a bead of epoxy is applied to both the fiber tube flange **34** and the tube **32** epoxy fill hole **60**. Our package allows its cover to be in place during the alignment.

The fiber tube flange **34** controls the fiber angle at 90°. The package normally does not require angular alignment. Only translational alignment is needed.

Our uptapered fiber **30** requires an angular alignment of one half degree of arc. If the tolerances listed in Table I are maintained, and the **L1** position is checked and adjusted properly, the package will achieve this.

If these tolerances are not strictly held, good alignments are still possible, but the active alignment process must include angular alignment of the fiber **30** rather than just lateral alignment. This is done by varying the angle of the fiber tube **32** slightly about the horizontal and vertical axes. Epoxy may still be used to join **62** the flange to the package.

The completed package offers both temperature and optical power monitoring of the semiconductor **22**. Temperature regulation is provided by the thermoelectric cooler **26** as controlled by the thermistor **30**. Optical power monitoring is provided by the rear facet detector **72** that measures the lost light emitting from the rear of the laser **22**.

High frequency capability is provided by several features. A 50 ohm impedance microstrip line transmits the high speed signal between the laser and an SMA microwave connector **54**. A short wirebond between the semiconductor **22** and microstrip **56** minimizes parasitic capacitances and inductances. In FIG. *2a*, the microstrip line **56** opposite the SMA connector **54** provides for only mechanical positioning and serves no electrical function.

A second embodiment (not shown) is the same as the first embodiment except that the semiconductor laser **22** is mounted epi-up. This means that the light emitting region **23** is now near the top surface of the semiconductor die. The pedestal height **17** must be reduced to offset the thickness of the semiconductor **22** and bring the light-emitting spot **23** back to the axis of the lens **24**.

This embodiment offers two advantages over the first embodiment:

- The active region **23** features in the semiconductor are directly visible, allowing more precise alignment to the lateral reference mark **38** on the pedestal **16**.
- It allows for epi-up bonding of semiconductor material reducing diebonding yield loss present with some diebonding solders and laser structures.

The comparative disadvantage of this design is that the wafer thickness now becomes a controlling optical tolerance requiring an additional wafer thinning pro-

cessing step or alternatively a set of calibrated carriers with different known pedestal heights.

It is possible to vary the design of package **10** while preserving elements of our invention. Variations could be both internal or external to the package housing. The material comprising the package housing **12** may be metal, ceramic or plastic.

EXTERNAL VARIATIONS

The diameter of the uptapered-fiber **30** may be increased requiring a greater magnification from the lens **24**. The greater magnification is achieved by using a different lens or lens position. This variation, of increasing the magnification, results in further reduction of the lateral positional tolerance.

The length of the thick section of the uptapered-fiber **30** may be altered. A shorter length section would make a more compact package.

The fiber **30** may be held by a variety of different shaped holders but it always needs to be held rigidly. It is likely that it would always require some kind of flange type attachment **34** such as the one in FIG. **1** to maintain stability.

Some commercial fibers are supplied with flange shaped connectors on the end and it is likely that uptapers will be supplied this way once the uptapers become commercially available. If this happens, the uptapered package may be designed to accommodate the commercial flange rather than have a special package flange.

The mode of fastening the fiber may be varied. Different types of epoxies, polyesters, solders or welds may be used. In some circumstances it may be possible to screw, crimp, or even use an amalgam to attach the fiber holder to the package.

INTERNAL VARIATION

The package is made more compact by using stronger, shorter focal length lenses. In this case, the end of the uptapered-fiber is placed closer to the lens.

In conclusion, we have realized the first laser package to incorporate an uptapered fiber pigtail. Because of the relaxed alignment tolerances afforded by the uptapered, external alignment and attachment of the fiber can be implemented. The result is an easy-to-assemble, rugged package that is suitable for all local loop applications, and readily lends itself to automated packaging techniques.

What is claimed is:

1. A package for an optoelectronic semiconductor device having a photo-active element optically coupled to an uptapered single-mode optical fiber connecting said optoelectronic device to an external device, comprising:

- a housing to enclose the necessary components to convert electrical signals to optical signals;
- a substrate carrier having a solderable surface within said housing; an optoelectronic device having an photo-active element secured to said subcarrier;
- a lens, having a numerical aperture sufficient to access optically said photo-active element secured to said carrier a fixed distance from said photo-active element to yield a desired magnification of a light beam emanating from said photo-active element by expanding the size of said beam;
- an uptapered single-mode optical fiber extending from within said housing to the exterior of said housing through a port thereof, said optical fiber being positioned by active alignment;
- means to secure said uptapered optical fiber to said housing such that the uptapered end of said optical fiber is optically coupled through said lens to said photo-active element and the opposite end of said optical fiber is outside said housing; and
- a plurality of reference means on said housing and said carrier such that said optoelectronic device, said lens and said optical fiber are mechanically positioned with respect to one or more of said reference means; and such that uptapered said optical fiber is externally aligned and secured to said package.

2. The package of claim **1** wherein:

- said substrate carrier includes a pedestal integrally formed with said substrate;
- said optoelectronic device is mounted on said pedestal; and
- said reference means include the upper surface and one side surface of said pedestal, and a reference mark on said upper surface for alignment with a reference mark on said optoelectronic device.

3. The package of claim **1** wherein said reference means for mechanically positioning said lens on said carrier comprises:

- a pair of spaced apart lateral stops integrally formed with said carrier; and
- a pair of spaced apart axial stops integrally formed with said carrier;
- such that said lens is rigidly positioned between each pair of stops in alignment with said photo-active spot and said uptapered optical fiber.

4. The package of claim **1** wherein said lens is a graded index lens and is secured to said carrier with a moderate melting point solder.

5. The package of claim **1**, further comprising:

- a thermoelectric cooler positioned under said substrate carrier within said housing to maintain a stabilized temperature for said optoelectronic device.

6. An uptapered single-mode optical fiber package providing mechanically precise, stable alignment of an uptapered optical fiber with a semiconductor laser having a photo-active element within said package, comprising:

- a housing to enclose the necessary components to convert electrical signals to optical signals;
- a substrate carrier having a solderable surface within said housing;
- a plurality of reference means positioned on said housing and said substrate carrier;
- an optoelectronic laser device having a photo-active element and having a reference means, secured to said substrate carrier in alignment with a first set of corresponding reference means;
- a graded index lens, having a numerical aperture sufficient to access optically said photo-active element aligned with a second set of reference means and secured to said substrate a fixed distance from said photo-active element to yield a desired magnification of a light beam emanating from said photo-active element;
- an uptapered single-mode optical fiber extending from within said housing to the exterior of said housing through a port thereof for connection of said laser to a device external to said housing;
- fiber positioning means to mechanically align said uptapered optical fiber with respect to a third set of reference means and to support said uptapered

optical fiber in said aligned position, said optical fiber being positioned by active alignment and secured to said fiber positioning means such that the uptapered end of said optical fiber is optically coupled through said lens to said photo-active element of said laser and the opposite end of said optical fiber is outside said housing, and such that the distance between said uptapered end of said optical fiber and said lens and the distance between said lens and said active element is prespecified by said reference means; and

said fiber positioning means being secured to said package with said optical fiber in said aligned position.

7. The package of claim 6 wherein:

said substrate carrier includes a pedestal integrally formed with said substrate;

said optoelectronic device is mounted on said pedestal; and

said reference means include the upper surface and one side surface of said pedestal, and a reference mark on said upper surface for alignment with a reference mark on said optoelectronic device.

8. The package of claim 6 wherein said reference means for mechanically positioning said lens on said carrier comprises:

a pair of spaced apart lateral stops integrally formed with said carrier; and

a pair of spaced apart axial stops integrally formed with said carrier;

such that said lens is rigidly positioned between each pair of stops in alignment with said photo-active spot and said uptapered optical fiber.

9. The package of claim 6 wherein said graded index lens is secured to said substrate with a moderate melting point solder.

10. The package of claim 6, further comprising:

a thermoelectric cooler positioned under said substrate carrier within said housing to maintain a stabilized temperature for said semiconductor laser device.

11. The package of claim 6 wherein said reference means for mechanically positioning said uptapered optical fiber further comprise:

a reference mark within said housing to position the uptapered end of said optical fiber; and

a reference surface on the side wall of said housing through which said fiber passes.

12. The package of claim 11 further comprising:

a support means for said uptapered optical fiber, said support means being positioned at the port of said housing through which said optical fiber extends.

13. The package of claim 12 support wherein said support means for said uptapered optical fiber comprises:

a fiber tube adapted to receive an uptapered optical fiber in a fiber-receiving position which is determined by the active element-to-lens spacing, such that said uptapered optical fiber may be optically coupled to said active element of said semiconductor laser through said lens;

said optical fiber in said fiber tube being actively aligned with said photo-active element and secured in said aligned position; and

a fiber tube flange to secure said fiber tube to said housing with said fiber in alignment with said semiconductor and with said third set of reference means.

14. An improved package providing for the precise, secure alignment of an uptapered single-mode optical fiber to a single packaged optoelectronic laser device having a light-emitting source, said package including:

a housing to enclose the necessary components to convert electrical signals to optical signals;

a substrate carrier having a solderable surface within said housing;

an optoelectronic laser device having a light-emitting source positioned on and secured to said substrate;

a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic array; wherein the improvement comprises:

a plurality of reference means located on said housing and said substrate;

a portion of said substrate being adapted to receive said laser and said lens;

said optoelectronic laser device being positioned mechanically with respect to a first set of reference means;

said graded index lens being mechanically positioned with reference to a second set of reference means and secured to said substrate of a fixed distance from said laser such that the light beams from said light-emitting source are magnified and the spacing between said beams is expanded;

said uptapered optical fiber being mechanically positioned with respect to a third set of reference means and actively aligned with said light-emitting source by optically coupling the thick end of said uptapered single-mode optical fiber to a light beam emanating from said laser after said beam has been magnified by said lens; and

said means to secure said uptapered optical fiber to said package after alignment.

15. The package of claim 14 wherein said reference means for mechanically positioning said uptapered optical fiber further comprise:

a reference mark within said housing to position the uptapered end of said optical fiber; and

a reference surface on the side wall of said housing through which said fiber passes.

16. The package of claim 15 wherein said means to secure said uptapered optical fiber to said housing comprises:

support means for said uptapered optical fiber, said support being positioned and secured at the port of said housing through which said uptapered optical fiber extends.

17. The package of claim 16 wherein said support means further comprises:

a fiber tube adapted to receive an uptapered optical fiber in a fiber-receiving position which is determined by the photo-active element-to-lens spacing, such that said uptapered optical fiber may be optically coupled to said photo-active element through said lens;

said uptapered optical fiber in said fiber tube being positioned with respect to said reference means, actively aligned with said photo-active element, and secured in an aligned position within said fiber tube;

means to secure said fiber tube to said housing with said fiber in its aligned position.

18. The improved package of claim 14 wherein said alignment further comprises:

a fiber tube adapted to receive said uptapered optical fiber and to position said fiber with reference to said third set of reference means;

said graded index lens having a predetermined magnification factor being positioned and rigidly secured such that a beam between said optoelectronic laser and said optical fiber passes through the center of said lens;

the position of said lens being determined by the precise location of said light-emitting source as determined by said first set of reference means and the precise location of said second set of reference means such that said activated light-emitting sources as magnified by said graded index lens are coupled to said uptapered fiber; and

said uptapered optical fiber being secured to said package such that said optical fiber is positioned to be coupled with a beam of known location and size emanating from said activated light-emitting source.

19. The improved package of claim **18** wherein said optical fiber tube is secured in said aligned position to said housing by a fiber tube flange.

20. The improved package of claim **18** wherein said graded index lens is secured to said substrate with a moderate melting point solder.

21. The improved package of claim **18** wherein said optical fibers are secured in said fiber tube by a room temperature curing epoxy.

22. The improved package of claim **18** further comprising:

a fiber tube flange adapted to receive an uptapered optical fiber in said a fiber-receiving tube in a position which is determined by the laser-to-lens spacing, such that said uptapered optical fiber may be optically coupled to a correspondingly positioned light-emitting source through said lens;

said uptapered optical fiber in said fiber tube holder being actively aligned with said light-emitting source by the alignment of its optical fiber tube with the corresponding light-emitting source; and

said fiber tube holder being secured in its aligned position with epoxy.

23. The improved package of claim **14** further comprising:

a thermoelectric cooler positioned under said substrate carrier within said housing to maintain a stabilized temperature for said optoelectronic laser device.

24. The improved package of claim **14** wherein:

said substrate carrier includes a pedestal integrally formed with said substrate;

said optoelectronic device is mounted on said pedestal; and

said reference means include the upper surface and one side surface of said pedestal, and a reference mark on said upper surface for alignment with a reference mark on said optoelectronic device.

25. The improved package of claim **14** wherein said reference means for mechanically positioning said lens on said carrier comprises:

a pair of spaced apart lateral stops integrally formed with said carrier; and

a pair of spaced apart axial stops integrally formed with said carrier;

such that said lens is rigidly positioned between each pair of stops in alignment with said photo-active spot and said uptapered optical fiber.

26. The improved package of claim **14** wherein said reference means for mechanically positioning said uptapered optical fiber further comprise:

a reference mark within said housing to position the uptapered end of said optical fiber; and

a reference surface on the side wall of said housing through which said fiber passes.

* * * * *

United States Patent [19]

Boudreau et al.

[11] **Patent Number: 4,957,342**

[45] **Date of Patent: Sep. 18, 1990**

[54] **SINGLE-MODE OPTICAL FIBER ARRAY PACKAGE FOR OPTOELECTRONIC COMPONENTS**

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[73] Assignee: **GTE Laboratories Incorporated,** Waltham, Mass.

[21] Appl. No.: **444,500**

[22] Filed: **Nov. 30, 1989**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 439,761, Nov. 20, 1989.

[51] **Int. Cl.**5 .... **G02B 6/32;** G02B 6/36

[52] **U.S. Cl.** **350/96.18;** 350/96.20

[58] **Field of Search** 350/96.10, 96.15, 96.18, 350/96.20, 96.21, 320

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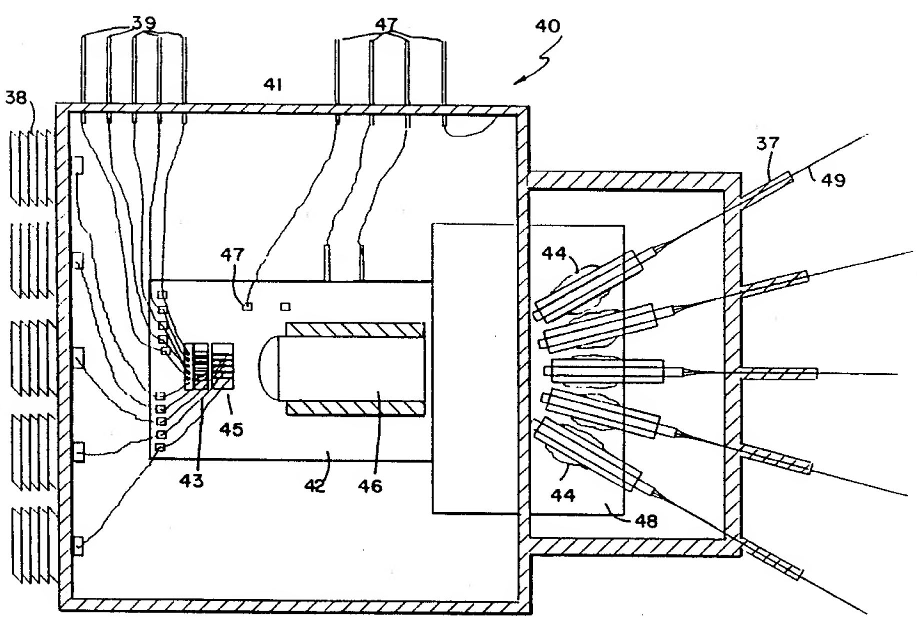
Primary Examiner—Akm Ullah

Attorney, Agent, or Firm—James J. Cannon, Jr.; Victor F. Lohmann, III

[57] **ABSTRACT**

A package for an optoelectronic array device having an array of n active elements optically coupled to an array of n single-mode optical fibers which connect said optoelectronic array to an external device includes a housing having a solderable substrate to which the array device is secured, a graded index lens also secured to said array at a distance calculated to provide a known magnification of light beams emanating from said array and n uptapered single-mode optical fibers actively aligned to said magnified light beams to achieve optimal optical coupling to said optoelectronic array. The package optionally includes a multifiber holder having precisely calculated spacing based on the spacing of said active elements which are usually semiconductor lasers and the magnification of said lens. For a two-dimensional surface array, the package includes a mandrel to position the uptapered optical fibers.

49 Claims, 8 Drawing Sheets



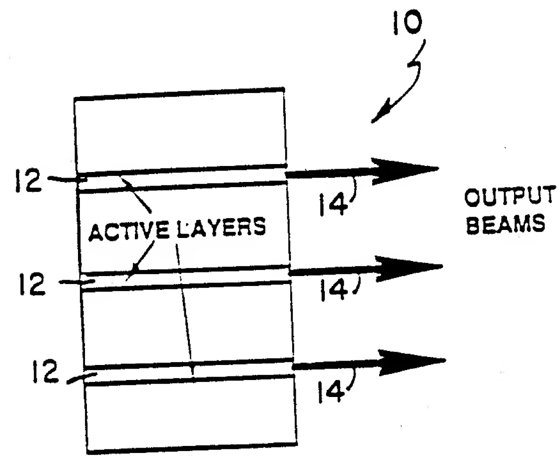


FIG. 1a

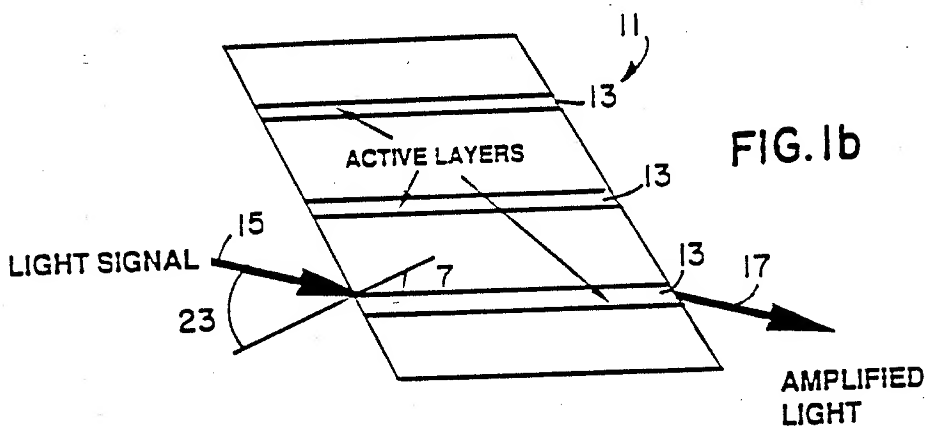


FIG. 1b

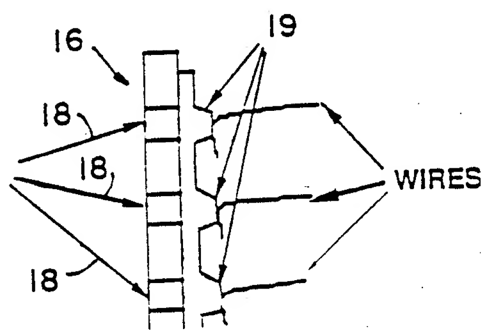


FIG. 1c

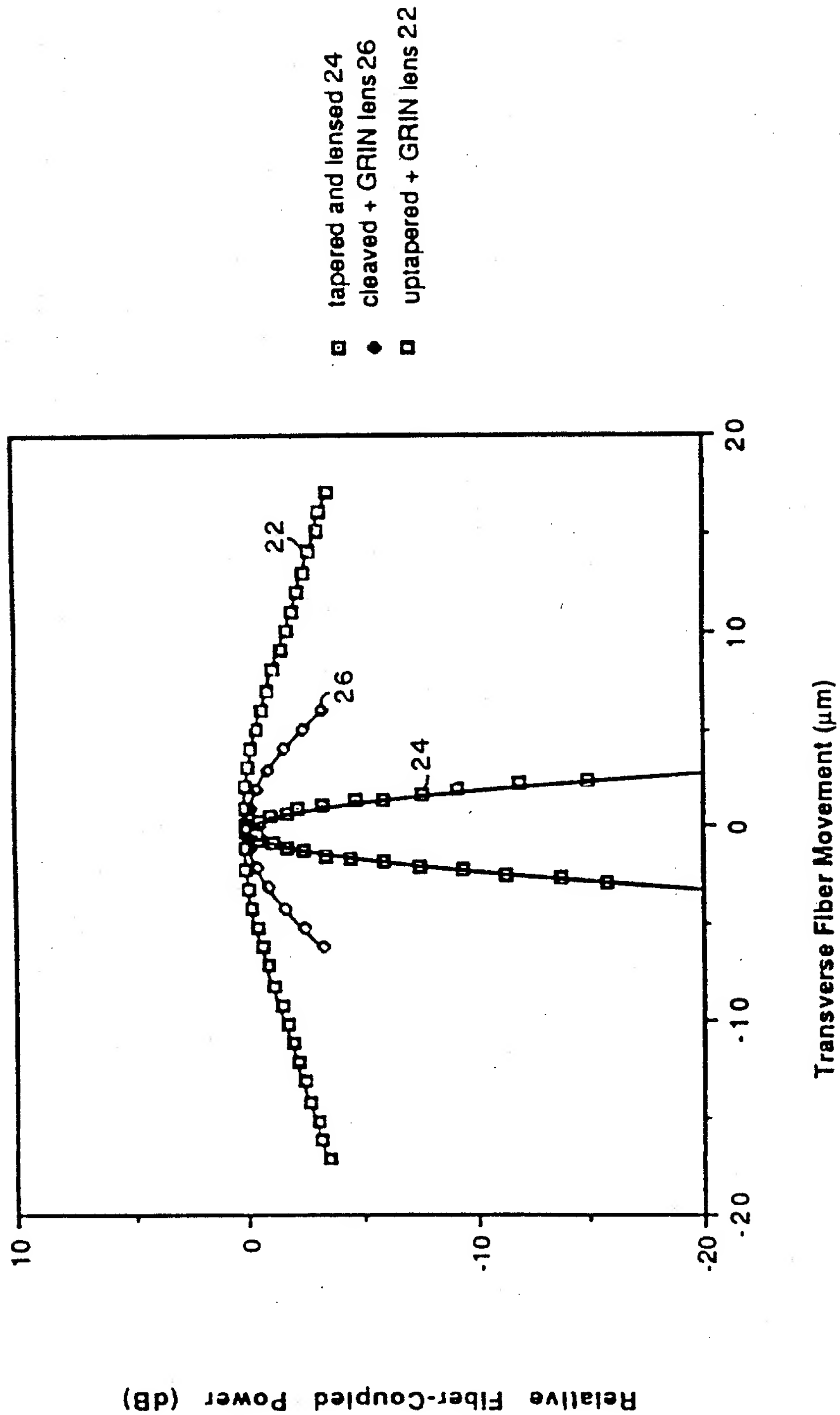

tapered and lensed 24
cleaved + GRIN lens 26
uptapered + GRIN lens 22
22
26
24
10
0
-10
-20
-20
-10
0
10
20
Transverse Fiber Movement (μm)
Relative Fiber-Coupled Power (dB)

FIG. 2

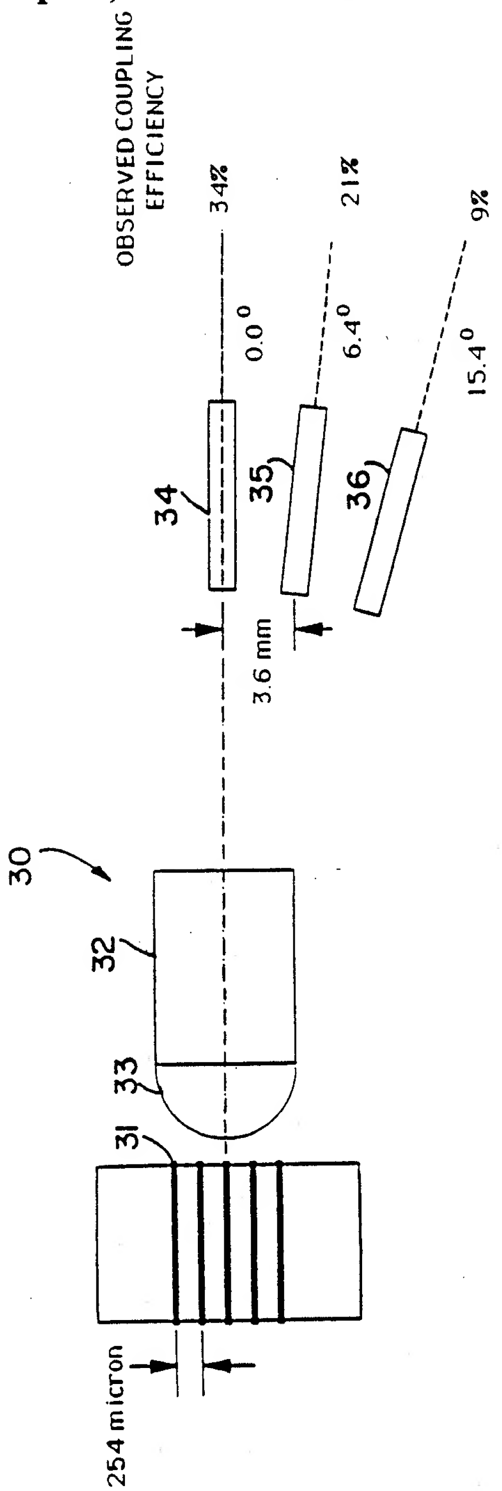

OBSERVED COUPLING EFFICIENCY
34%
21%
9%
0.0°
6.4°
15.4°
34
35
36
3.6 mm
30
32
33
31
254 micron

FIG.3

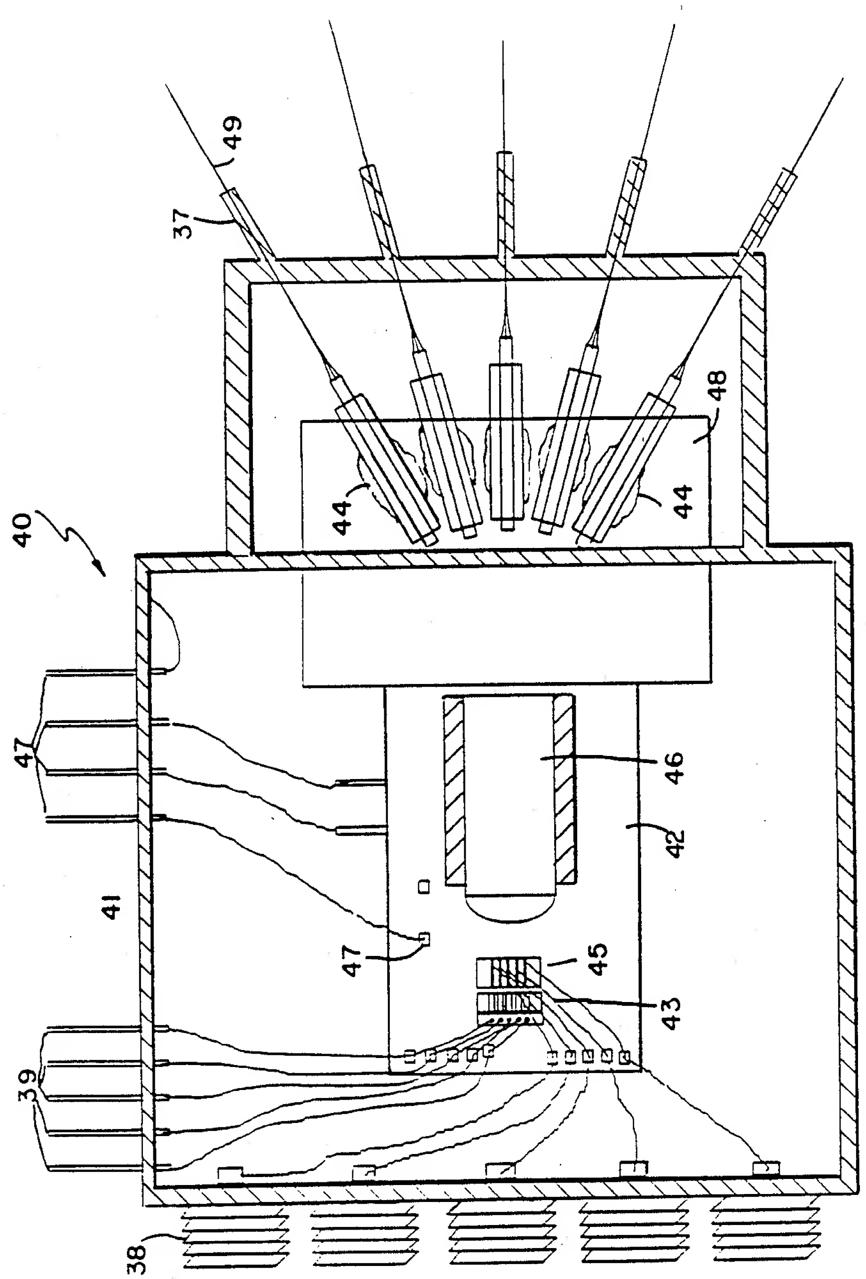


FIG. 4

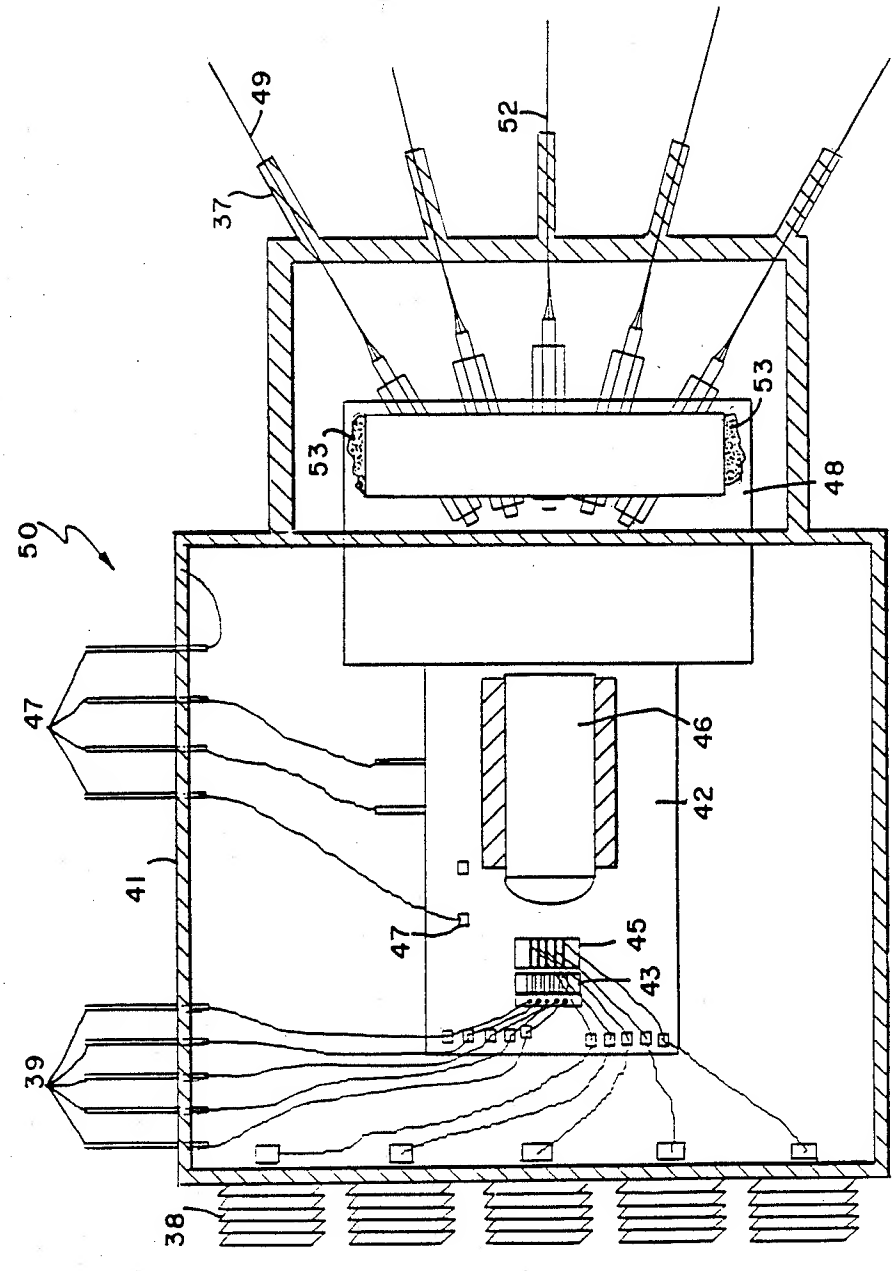


FIG. 5

FIG. 6A

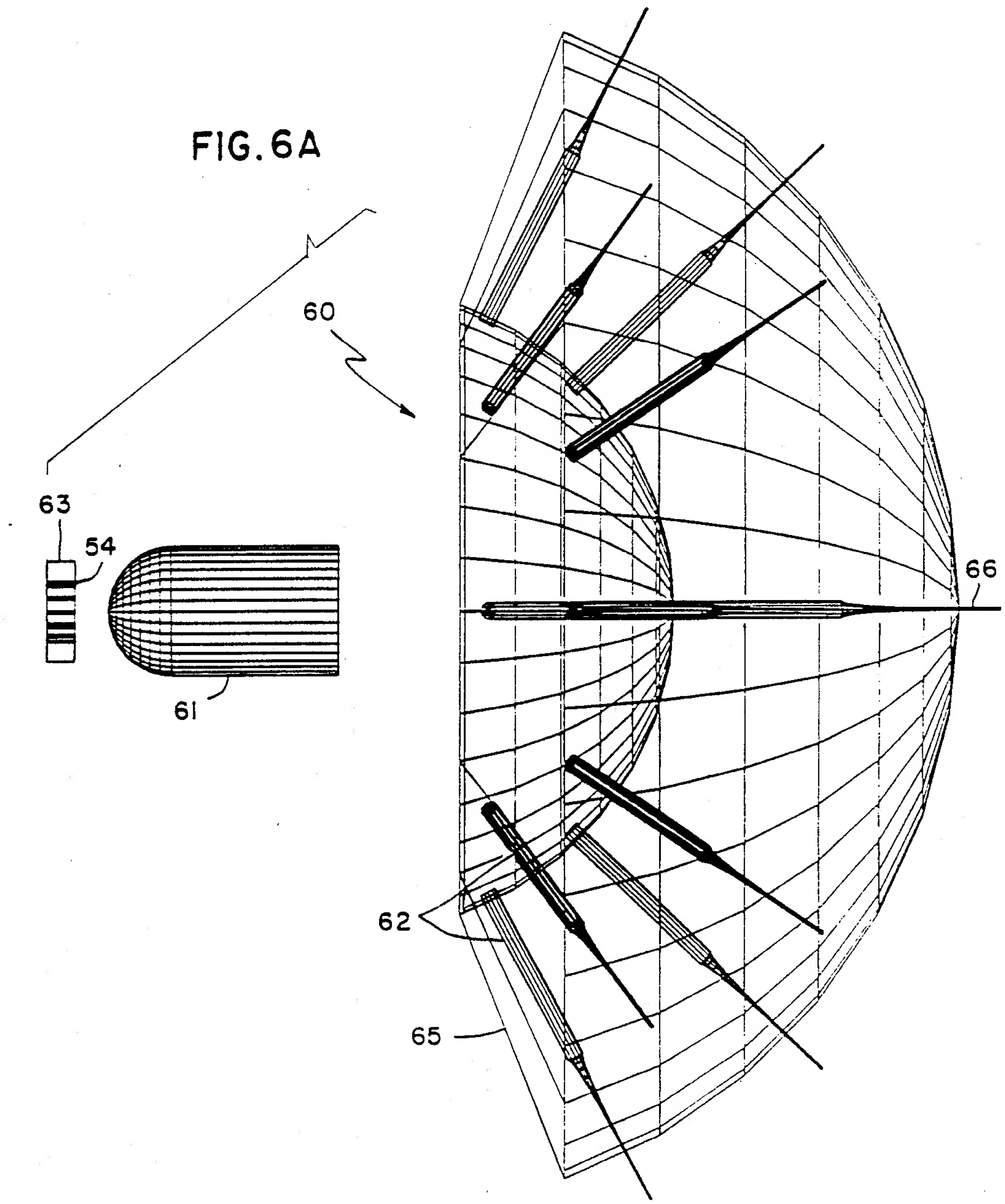


FIG. 6B

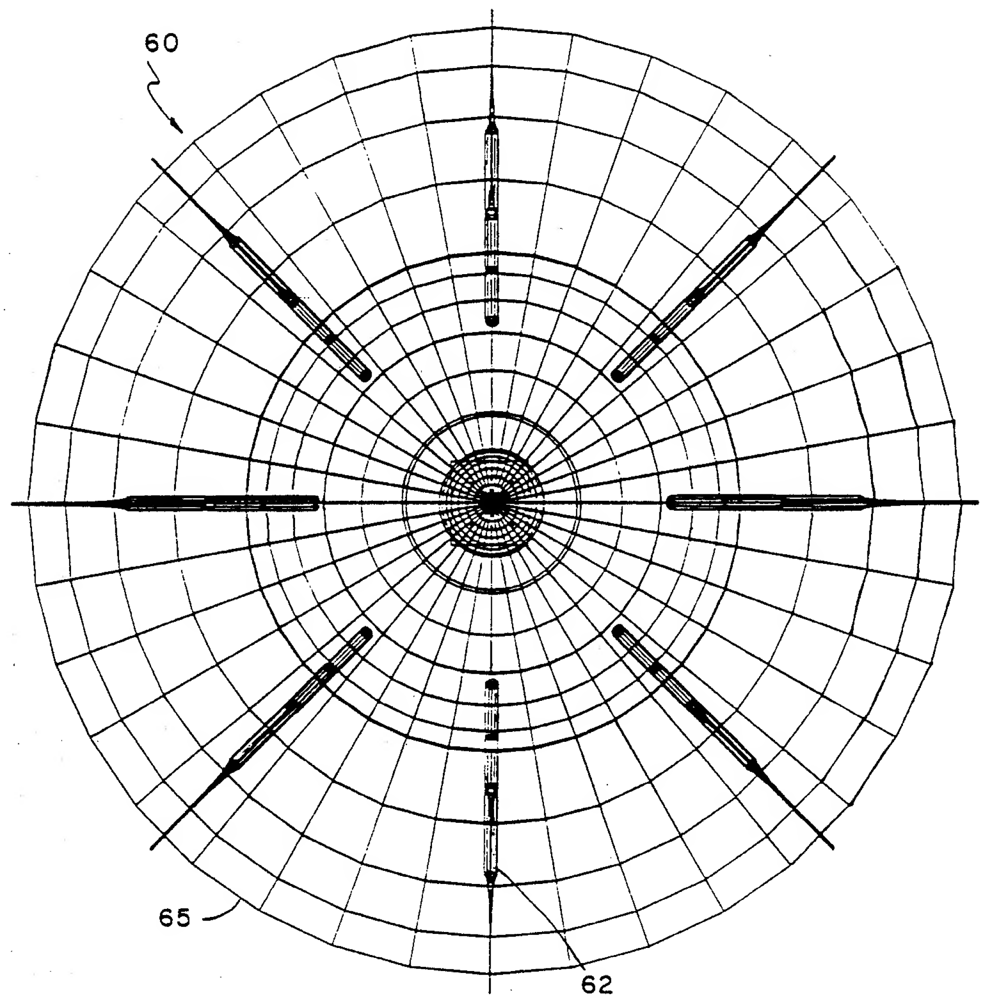
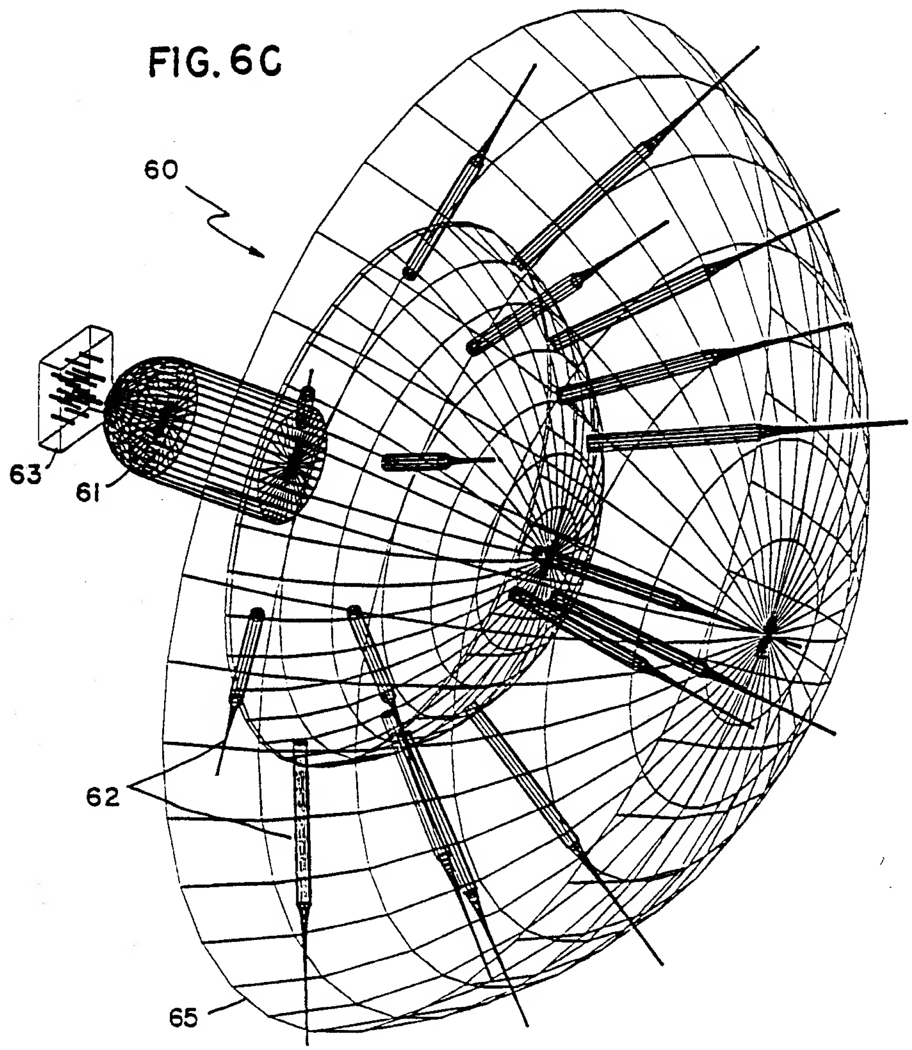


FIG. 6C



SINGLE-MODE OPTICAL FIBER ARRAY PACKAGE FOR OPTOELECTRONIC COMPONENTS

CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of a prior pending application entitled "A Method of Aligning and Packaging an Optoelectronic Component with a Single-Mode Optical Fiber Array," filed by the same inventors on Nov. 20, 1989, Ser. No. 07/439,761, and assigned to the same assignee as this application now allowed.

BACKGROUND OF THE INVENTION

This invention related to packaging of optoelectronic components which generate or process signals that pass through optical fibers. In particular, it addresses the critical need for providing stable, low-cost alignment of multiple single-mode optical fibers to a single packaged device, such as a semiconductor array of laser amplifiers, lasers or photodetectors. Such devices have closely spaced active regions to which the optical fibers must be coupled.

An optoelectronic package is a container or housing that provides protection and support for both active and passive components contained within it. These components and their interconnection represent an optical-electrical circuit and define the function of the package. The package also includes a means of connecting the internal components with the external environment, usually as electrical feed-through and optical fiber. Our invention is concerned with the optical fiber and how it is connected to the components within the package.

To make an optical connection between an optical fiber and an optoelectronic component within a package, it is necessary to position or align the optical fiber in a way that allows efficient coupling between the optical fiber and the optoelectronic component. The precision needed for the alignment depends on the size of the light-emitting or light receiving elements, the type of optical fiber, and any type of focusing or defocusing elements which may be present. Optical fiber transmits light through its inner core, which is much smaller than the diameter of the optical fiber. There are two classes of optical fiber presently used in packaging semiconductor devices: single-mode and multi-mode, with typical core diameters of about 10 microns and 50 microns, respectively. Many telecommunication applications use single-mode optical fiber because of the superior bandwidth arising from its reduction of mode partition noise.

The prior art for multi-fiber array alignment to a single package is predominantly concerned with the easier task of coupling large-core multi-mode optical fiber to relatively large light sources and detectors. These alignments are less sensitive to position and can often be done with grooved parts and epoxy to fasten the optical fiber. This technology is acceptable for short length optical fiber links in local area networks or computers, but not for telecommunications.

Connecting single-mode optical fiber to semiconductor devices is difficult. Extremely tight tolerances, on the order of one micron, are needed due to the small size (about one micron) of the active region and the small optical fiber core. Optical fibers are usually actively aligned to the semiconductor component. This means that for the semiconductor laser, the laser is electrically biased to emit light. The optical fiber is then aligned to a position that maximizes its reception of light, a condition monitored by coupling a photodetector to the opposite end of the optical fiber. The manipulation of the optical fiber is usually done with a suction-tipped micromanipulator arm with piezo-electric controls having submicron positional sensitivity. Additional problems arise when more than one optical fiber needs to be coupled to a single device, since this necessarily entails either simultaneous alignment or sequential alignment to multiple optical fibers. Simultaneous alignment is a situation in which each optical fiber must be physically connected to a manipulator of some kind, the optical fibers then moved together and then held in position all at the same time. Sequential alignment is the process of aligning separate optical fibers, one by one. Alignment of one optical fiber often disrupts previously aligned optical fibers such that the overall yield of the process may be low. For array alignments, the active elements may be only 150 to 300 microns apart on the semiconductor, leaving little room for holding the optical fibers, which normally have outside diameters (core plus cladding) of 125 microns. The optical fibers would be nearly in contact with each other when positioned for direct coupling to the active regions on the semiconductor.

Once single-mode optical fibers are aligned, they are usually fixed in their position by laser welding or soldering. It has been shown that the application of a graded index (GRIN) lens with an uptapered optical fiber will increase the alignment tolerances to the extent that the more easily made epoxy attachment can be made at room temperature and without the cost of laser welding. This advantage is present in our invention as applied to arrays.

SUMMARY OF THE INVENTION

The principle object of the present invention is to provide an optoelectronic component package in which multiple single-mode optical fibers are efficiently optically coupled to an array of closely spaced active semiconductor elements.

A second object of the present invention is to provide such a package for optical connections that permit independent transfer of telecommunications data and information for each semiconductor element.

Another object of this invention is to provide such a package that is not limited to one-dimensional arrays, such as standard edge emitters and detectors, but can also be used for two dimensional arrays, such as surface emitters and detectors.

Still a further object of the present invention is to provide such a package having a predictable, reproducible location of the optical fibers for maximum coupling efficiency, so that an entire array of optical fibers can be simultaneously aligned, taking maximum advantage of the extreme precision of the semiconductor array dimensions, and allowing for assembly line mass production of packaged optoelectronic components.

A further object of the invention is to provide a package which offers the opportunity to introduce optical filtering of the separate beams in an array, due to the increased space between the lens and the fibers.

In a first aspect of the invention, a package for an optoelectronic array device having an array of active elements optically coupled to an array of single-mode optical fibers connecting said optoelectronic array to an

external device includes a housing to enclose the necessary components to convert electrical signals to optical signals. A substrate carrier within said housing has a solderable surface. An optoelectronic array device having n active elements is secured to said substrate. A graded index lens, having a numerical aperture sufficient to access optically said n active elements and having a curvature on one end closest to said optoelectronic array, is secured to said substrate a fixed distance from said optoelectronic array of active elements to yield a desired magnification of light beams emanating from said active elements. An array of n uptapered single-mode optical fibers extends from within said housing to the exterior of said housing through a port thereof, said optical fibers being positioned by active alignment and secured to said substrate such that the uptapered end of each of said optical fibers is optically coupled through said lens to one of said n active elements of said optoelectronic array and the opposite end of said optical fiber is outside said housing, and such that the distance between said optical fibers matches the distance between light beams emanating from said active elements.

In a second aspect of the invention, a single-mode optical fiber array package providing precise, stable alignment of an array of optical fibers with a two-dimensional semiconductor surface array having a plurality of active elements within said package, includes a housing to enclose the necessary components to convert electrical signals to optical signals. A substrate carrier having a solderable surface is situated within said housing. An optoelectronic array device having n active elements is secured to said substrate. A graded index lens, having a numerical aperture sufficient to access optically said active elements and having a curvature on one end closest to said array, is secured to said substrate a fixed distance from said array of active elements to yield a desired magnification of light beams emanating from said active elements. An array of n uptapered single-mode optical fibers extends from within said housing to the exterior of said housing through a port thereof for connection of said surface array to a device external to said housing. A mandrel is provided to position and support said n uptapered optical fibers, said optical fibers being positioned by active alignment and secured to said mandrel such that the uptapered end of each of said optical fibers is optically coupled through said lens to one of said n active elements of said surface array and the opposite end of said optical fiber is outside said housing, and such that the distance between said optical fibers matches the distance between light beams emanating from said active elements. Said mandrel is potted to said package in said aligned position of said optical fibers.

In a third aspect of the invention, an improved package providing for the precise, secure alignment of multiple single-mode optical fibers to a single packaged optoelectronic array device having an array of at least two light-emitting sources includes a housing to enclose the necessary components to convert electrical signals to optical signals. A substrate carrier having a solderable surface is within said housing. An optoelectronic array device having n light-emitting sources secured to said substrate. A portion of said substrate is adapted to receive said array of optical fibers. A graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic array is secured to said substrate of said package a fixed distance from said optoelectronic array such that the light beams from said light-emitting sources are magnified and the spacing between said beams is expanded. Said optical fibers are actively aligned with said light-emitting sources by optically coupling the thick end of one uptapered single-mode optical fiber to each light beam emanating from said optoelectronic array after said beam has been magnified by said lens. Said optical fibers are secured to said fiber stage of said package after alignment.

In another aspect of the invention, the improved package provides a multi-fiber holder adapted to receive n uptapered optical fibers in fiber-receiving positions which are determined by the optoelectronic array-to-lens spacing, such that each of said n uptapered optical fibers may be optically coupled to one correspondingly positioned light-emitting source through said lens. Said n optical fibers in said multi-fiber holder are actively aligned with said light-emitting sources by the alignment of its central optical fiber with the corresponding central light-emitting source. Said multi-fiber holder is secured in its aligned position with epoxy.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1***a* is a schematic top view of an array of three semiconductor lasers;

FIG. **1***b* is a schematic top view of an array of three semiconductor laser amplifiers;

FIG. **1***c* is a schematic side view of an array of three semiconductor optical detectors;

FIG. **2** is a graph showing the transverse sensitivities of the various single-mode optical fiber couplings to a semiconductor laser;

FIG. **3** is a diagrammatic view of a first embodiment of the method of the invention illustrating the use of a GRIN lens to couple an array of uptapered optical fibers to a semiconductor laser array;

FIG. **4** is a top cut-away view of a first embodiment of an optoelectronic package embodying the method illustrated in FIG. **4**;

FIG. **5** is a top cut-away view of a second embodiment of an optoelectronic package, similar to that of FIG. **4**, but further including a multi-fiber holder; and

FIGS. **6***a*, **6***b* and **6***c* are side, end and perspective views respectively of an embodiment of an optoelectronic package in which uptapered optical fibers are coupled through a lens to a seventeen-element, two-dimensional surface array.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention pertains to packages for optoelectronic array devices which provide stable alignment of multiple single-mode optical fibers to the component using a method for quick and efficient optical coupling of multiple single-mode optical fibers to an array of closely spaced active semiconductor elements. The method has been disclosed and claimed in a prior application entitled "A Method of Aligning and Packaging an Optoelectronic Component with a Single-Mode Optical Fiber Array,", filed Nov. 20, 1989, Ser. No. 07/439,761, assigned to the assignee of this application and having the same inventors now allowed. Examples of semiconductor devices which require multiple optical fibers set in an array are shown in FIGS. **1***a*, **1***b* and **1***c*. FIG. **1***a* shows an array **10** of semiconductor lasers **12**, used as light sources for such purposes as parallel processing. An optical fiber must be coupled to each

lasing output beam **14**. FIG. **1**b shows an array **11** of optical amplifiers **13**, which receive light at one end and output the amplified light at the other end. One array of optical fibers **15** must couple the light signals into the optical amplifiers, and another array of optical fibers **17** must couple the amplified output. FIG. **1**c shows an array **16** of detectors **19**. One array **18** of optical fibers must couple the light signals into these detectors **19**.

FIG. **2** shows coupling performance, that is, the effect on relative fiber-coupled power and dB of transverse fiber movement, between a single-mode optical fiber and a high speed laser, a typical telecommunications component. For conventional tapered and lensed optical fibers, shown on line **24**, the positional sensitivity can be as little as one micron, a size much smaller that the parts themselves. FIG. **2** also shows the use of an uptapered optical fiber and a graded index (GRIN) lens, line **22**. This uptapered optical fiber system has the advantage of relaxing the lateral positional tolerances of the optical fiber at the expense of tightening the angular tolerances. FIG. **2** also shows the third case where a GRIN lens is used with a standard cleaved optical fiber, line **26**. This is an intermediate case of positional sensitivity, but is considered unfavorable for arrays because the magnification is insufficient. With all methods, problems are compounded when more than one single-mode optical fiber must be aligned to the same package in an array. By reducing the positional sensitivity, it is possible to achieve the necessary yield improvement required for doing array alignments.

The package of this invention uses a lens, with a sufficient numerical aperture and magnification, in conjunction with uptapered single-mode optical fiber. The alignment technique takes advantage of the relaxed mechanical tolerance and increased fiber-to-fiber spacing arising from the magnification provided by the lens and the larger cored uptapered fiber optics. Such optical connections then permit independent transfer of telecommunications data and information for each semiconductor element.

Specifically, this invention provides a new package for optically coupling multiple single-mode optical fibers to a single packaged optoelectronic array device using a single lens with the array of semiconductor elements in order to magnify the images of the various active elements to expand the spacing between them as well as their size. These separate images are then coupled to an array of uptapered optical fibers. This magnification greatly facilitates mechanical alignment and coupling of the semiconductor elements to the associated array of optical fibers by relaxing mechanical tolerances associated with the positions of the rays of light coming from the multiple lasers. It also separates the positions of the rays sufficiently to allow space for mechanical fixturing to hold the separate optical fibers to receive the light.

Uptapered optical fibers are used because the effect of magnification not only increases the spacing between the separate rays of light but also increases the size of the separate beams or spots. These beams are best collected on the thick end of the uptapered fiber, where the size of the optical fiber best matches the size of the separate beams. For example, a typical uptapered optical fiber may have a core that is ten times larger on its thick end than the single-mode optical fiber that it tapers down to. This optical fiber is used with a lens that magnifies everything tenfold, both the spot size of the beam as well as the spacing between beams. This effect facilitates the alignment when assembling an optoelectronic package, since the magnification typically results in a spacing of about three mm between separate light beams.

This description of the preferred embodiments also applies to the case of an array of detectors, in which case the light path is simply in the reverse direction, passing from the optical fiber to the semiconductor.

Simultaneous alignment is also possible with these systems because the location of the semiconductor array beams can be known with high precision relative to the central beam in the array. This is because the semiconductor elements are usually patterned on the semiconductor with photolithography to a high level of precision, about one micron, and the lens projects a precise image of this pattern towards the fibers. If a lens with known magnification is first positioned rigidly in a central specified location, then the locations of the other projected beams are known. Alignment to this central beam automatically aligns other optical fibers held collectively in a fixture engineered with the geometry set by the known magnification determined by the lens. Tolerance errors are also greatly reduced if only a single lens is used, eliminating errors incurred from alignment of multiple lenses to each other.

One limitation of the invention that must be considered is the issue of numerical aperture (N.A.) of the lens. This is analogous to field of view through a microscope or a pair of binoculars. The numerical aperture of the lens is defined as:

$$N.A. = n^{\circ} \sin a,$$

where

a = lens acceptance angle, and

n° = index of refraction of the lens.

This limits the number of semiconductor elements arranged in a line that can be accessed optically. A lens with the largest possible numerical aperture should be chosen. A good value for the numerical aperture is about 0.6, and all our experimentation was conducted with a lens having this numerical aperture. Using this lens, we were able to easily couple to an in-line five-element array.

One special feature of our invention is that the effect of the numerical aperture limitation can be eliminated or reduced when used in conjunction with a surface emitting array since the field of view is two-dimensional. Presently, no schemes exist for coupling single-mode optical fiber to semiconductor surface arrays. However, this method is valuable in making that possible by relaxing positional tolerances. Since the system works well with a five-element in-line array, it follows that it works for a seventeen-element surface array having elements arranged within a numerical aperture limited circle on the semiconductor. The projected and magnified image of the surface array replicates the high precision of the placement of the array elements, facilitating the fabrication of a support structure or mandrel which supports the uptapered optical fibers. Simultaneous alignment to all optical fibers is performed by first aligning the center fiber, and then rotating the mandrel to align the rotational orientation.

FIRST EMBODIMENT

The first embodiment of this invention is the method of using a GRIN lens to couple an array of uptapered optical fibers to a semiconductor laser array. This is

shown in FIG. 3. The semiconductor laser array 30 is a single solid-state microelectronic chip with five separate laser elements 31 on it. The GRIN lens 32 used is a SELFOC pch 1.8–0.22 Micro Lens (SML). It has a physical diameter of 1.8 mm and an overall length of 3.3 mm. A curvature 33 is present on the end of the lens closest to the laser array 30 in order to reduce distortions and increase the numerical aperture to 0.6. The lens 32 is centered on the laser array 30 and is located at a distance of about 0.37 mm from the laser array 30. A first uptapered optical fiber 34 in located about 15 mm away from the back of the lens 32. The spacing between lasers 31 in the array 30 is about 250 microns, while separation between uptapered optical fibers 34, 35, 36, as a result of the magnification, is about 3 mm. The separate light beams emerging from the lens 32 arrive at the uptapered optical fibers 34, 35, 36 at different angles, depending on the magnification and the displacement of the separate light sources from the centerline of the lens 32. For the five-element case shown, the outside beams arrive at about 15 degrees, as compared to 0 degrees for the central beam. When optically aligning this system, it is important to first rigidly fix the location of the GRIN lens 32 with respect to the laser array 30. This is done with a moderate melting point solder rather than a low melting point solder to reduce the creep of the parts. The magnification is highly dependent on the array-to-lens distance. For example, this lens produces magnifications of about 34, 9.7 and 4 for laser-to-lens distances of about 0.3, 0.4 and 0.6 mm respectively. The magnification is selected depending on the predetermined spacing desired between the separate uptapered optical fibers 34, 35, 36, or what would best match the spot size of the magnified beam and the uptapered optical fiber cores. In this embodiment, a magnification of about ten was used.

Alignment of the uptapered optical fibers 34, 35, 36 to the beam is done to a precision of about 0.5 degrees of arc. Since the uptapered optical fibers have a fairly long, narrow and rigid geometry, this tolerance is easy to achieve. Also, as shown in FIG. 2, the uptapered optical fiber has a more relaxed transverse positional tolerance compared to conventional optical fiber. In our test of this embodiment, the optical fibers 34, 35, 36 were actively aligned using a micromanipulator while the laser array was operating. The manipulator was capable of controlling the optical fiber position to a transverse tolerance of about five microns.

SECOND EMBODIMENT

The second embodiment of this invention is a package apparatus employing the method described in the first embodiment. This package 40, for use with a five-element laser array, is shown in FIG. 4. A metal housing 41, indicated by the dotted gray border in the diagram, encloses the necessary components that convert input electrical signals 38 to optical signals. A carrier 42 having a surface that is readily solderable, such as gold-plated copper or brass, is used to support the components. The photodetector monitor array 43 and its associated shadow mask to prevent crosstalk between monitored array outputs 39 is optional. Its function is to keep the laser output power constant, but it may not be necessary, depending on the lasers or the application.

As is common practice, the semiconductor array 45 is first diebonded to an efficient, thermally conductive heatsink, such as diamond or boron nitride. The unit is then located on the carrier 42 by soldering to either a pedestal or a reference mark. For package 40, this can be done to an accuracy of about 15 microns. The GRIN lens 46 is then located on the same carrier 42 with respect to the laser 45 using a mechanical stop of carrier 42, and soldered in place with a moderate melting point solder such as 62/36/2 SnPbAg eutectic which melts at 179 degrees C.

The carrier assembly is completed by adding the usual thermistor 47 and internal wirebonds. Finally, the carrier 42 is soldered to the top of a thermoelectric cooler (TEC) (not shown) which is located within the package housing 41. When the package is in operation, the TEC in conjunction with the thermistor is used to stabilize the operating temperature of the semiconductor 45 to maintain constant output power, a common practice. Wirebonding is performed to connect components on the carrier 42 to the output and input electrical pins.

As shown in FIG. 4, part of carrier 42 includes a section called the fiber stage 48. This is the part to which the uptapered optical fibers 49 attach. Fiber stage 48 is best as an integral part of carrier 42 to reduce small movements of the optical fiber 49 relative to lens 46.

The optical fiber alignment is done actively, as described earlier for single element semiconductors, except that the alignments are done sequentially and fastened into position with a room temperature curing epoxy to prevent disturbance of previously aligned optical fibers. The uptapered fiber optics relaxes the tight transverse tolerances sufficiently to allow for an epoxy fastening, as discussed earlier. Each alignment is done separately using the vacuum-tipped micromanipulator.

The package is completed by sealing a lid on it with epoxy and providing additional support for the optical fibers exiting the package through the fiber ports. The package is then tested and ready for delivery.

THIRD EMBODIMENT

The third embodiment is the package apparatus 50 and a method for doing a simultaneous alignment of the array of optical fibers. This is shown in FIG. 5. Package 50 and its assembly is basically the same as that described in the second embodiment, except that all the optical fibers are previously mounted in a multi-fiber holder 51. The geometry of the holder 51 is predetermined based on the laser array-to-lens spacing. Multi-fiber holder 51 is then aligned to the center optical fiber 52 only. Most of the error associated with the alignment of the other optical fibers is taken up in this first alignment. The central optical fiber alignment automatically positions the alignment of the other optical fibers because of the photolithographic precision of the active laser elements on the chip, as discussed before. Holder 51 is then epoxied in position as if it were a single optical fiber, and the package is completed as described earlier. This system sacrifices some precision in exactly locating each optical fiber in exchange for a process that requires less time to complete all alignments.

FOURTH EMBODIMENT

The fourth embodiment is package 60, resulting from the method of using the graded index lens 61 with uptapered optical fibers 62 to couple to elements 64 of two-dimensional surface array 63, as shown in FIGS. 6a, 6b and 6c. Since the numerical aperture of lens 61 accepts light from a two-dimensional surface in the same way as it does from a line of active elements, it

follows that the method will work to the same degree of precision and tolerance for other cases. As shown in the figures, light emitted from as many as seventeen elements **64** can be transmitted through lens **61** to optical fibers **62**. In practice, it is recommended that optical fibers **62** be held in a support mandrel **65**, as shown schematically in FIGS. **6a**, **6b** and **6c**. This allows for the use of the basic simultaneous alignment scheme as described above by first doing an active alignment to the center optical fiber **66**, and then rotating the mandrel **65** until a second optical fiber is aligned simultaneously, whence all of the outside fibers come into alignment. The entire mandrel **65** can then be potted into position with epoxy.

VARIATIONS

The major variation possible for our invention is the use of lenses other than a graded index lens. It is reasonable that a convex, planar-convex, or other partially convex lens may be substituted to achieve a similar magnification effect. It is also possible to use cleaved optical fibers rather than uptapered optical fibers and still get a functional package, but we prefer the uptapered optical fibers since they are used with more magnification. The system will work for local area networks (LAN) as well as computers, video and telecommunications. Finally, it should be remembered that our invention applies to any semiconductor array of active elements that needs coupling to a set of optical fibers, and is not limited to laser arrays described in the embodiments.

This invention offers substantial advantages. First, it is not limited to one-dimensional arrays, such as standard edge emitters and detectors, but can also be used for two-dimensional arrays, such as surface emitters and detectors. Secondly, the technique provides a predictable, reproducible location of the optical fibers for maximum coupling efficiency, so that the entire array can be simultaneously aligned. This takes maximum advantage of the semiconductor array dimensions. Thirdly, this method offers the opportunity to introduce optical filtering of the separate beams in an array, due to the increased space between the lens and the optical fibers. Finally, packages for optoelectronic components incorporating this method are feasible.

We claim:

1. A package for an optoelectronic array device having an array of optoelectronic active elements enclosed in a housing and secured to a substrate carrier having a solderable surface within said housing, said active elements optically coupled to an array of uptapered single-mode optical fibers connecting said optoelectronic array device to an external device, comprising:

a graded index lens, having a numerical aperture sufficient to access optically said active elements and having a curvature on one end closest to said optoelectronic array, secured to said substrate a fixed distance from said optoelectronic array of active elements to yield an appropriate magnification of the light beams emanating from said active elements; and

said array of uptapered single-mode optical fibers extending from within said housing to the exterior of said housing through a port thereof, said optical fibers being positioned by active alignment and secured to said substrate such that the uptapered end of each of said optical fibers is optically coupled through said lens to a respective one of said active elements of said optoelectronic array and the opposite end of said optical fiber is outside said housing, and such that each optical fiber is spatially aligned at its uptapered end to a respective one of the magnified light beams.

2. The package of claim **1** wherein said graded index lens is secured to said substrate with a moderate melting point solder.

3. The package of claim **1** further comprising:

a photodetector monitor array and shadow mask mounted on said substrate to prevent crosstalk between monitored outputs of said optoelectronic array and to maintain constant output power.

4. The package of claim **1** further comprising:

a heatsink secured to said substrate carrier; and

said optoelectronic array device is die-bonded to said heatsink.

5. The package of claim **1**, further comprising:

a thermoelectric cooler positioned under said substrate carrier within said housing to maintain a stabilized temperature for said optoelectronic array device.

6. The package of claim **1** wherein said optical fibers are secured to said substrate by a room temperature curing epoxy.

7. The package of claim **1** further comprising a support for said optical fibers, said support being positioned at the ports of said housing through which said optical fibers extend.

8. The package of claim **1** further comprising:

a multi-fiber holder adapted to receive said uptapered optical fibers in fiber-receiving positions which are determined by the active element array-to-lens spacing, such that each of said uptapered optical fibers may be optically coupled to one correspondingly positioned active element through said lens;

said optical fibers in said multi-fiber holder being actively aligned with said active elements by the alignment of its central optical fiber with the corresponding central active element; and

said multi-fiber holder being secured in its aligned position with epoxy.

9. The package of claim **1** further comprising a cover for said housing.

10. The package of claim **1**, wherein a ratio between the core sizes at the uptapered and downtapered ends of each optical fiber ranges from unit to ten.

11. A single-mode optical fiber array package providing precise, stable alignment of an array of uptapered single-mode optical fibers with a two-dimensional semiconductor surface array having a plurality of active elements within said package, said active elements being enclosed in a housing and secured to a substrate carrier having a solderable surface within said housing, comprising:

a graded index lens, having a numerical aperture sufficient to access optically said active elements and having a curvature on one end closest to said array, secured to said substrate a fixed distance from said array of active elements to yield an appropriate magnification of the light beams emanating from said active elements;

said array of uptapered single-mode optical fibers extending from within said housing to the exterior of said housing through a port thereof for connection of said surface array to a device external to said housing;

a mandrel to position and support said uptapered optical fibers, said optical fibers being positioned by active alignment and secured to said mandrel such that the uptapered end of each of said optical fibers is optically coupled through said lens to a respective one of said active elements of said surface array and the opposite end of said optical fiber is outside said housing, and such that each optical fiber is spatially aligned at its uptapered end to a respective one of the magnified light beams;

said mandrel being potted to said package in said aligned position of said optical fibers.

12. The package of claim **11** wherein said graded index lens is secured to said substrate with a moderate melting point solder.

13. The package of claim **11** further comprising:

a photodetector monitor array and shadow mask mounted on said substrate to prevent crosstalk between monitored outputs of said optoelectronic array and to maintain constant output power.

14. The package of claim **11** further comprising:

a heatsink secured to said substrate carrier; and

said surface array device is die-bonded to said heatsink.

15. The package of claim **11**, further comprising:

a thermoelectric cooler positioned under said substrate carrier within said housing to maintain a stabilized temperature for said surface array device.

16. The package of claim **11** further comprising:

a support for said optical fibers, said support being positioned at the ports of said housing through which said optical fibers extend.

17. The package of claim **11** wherein said mandrel comprises:

a multi-dimensional multi-fiber holder adapted to receive said uptapered optical fibers in fiber-receiving positions which are determined by the active element array-to-lens spacing, such that each of said uptapered optical fibers may be optically coupled to one correspondingly positioned active element on said two-dimensional surface array through said lens;

said optical fibers in said multi-fiber holder being actively aligned with said active elements by the alignment of its central optical fiber with the corresponding central active element and subsequent rotation of said multi-fiber holder until one other optical fiber is aligned simultaneously, resulting in alignment of said array of optical fibers; and

said mandrel is secured in its aligned position with epoxy.

18. The package of claim **11** further comprising a cover for said housing.

19. A single-mode optical fiber array package providing precise, stable alignment of an array of single-mode optical fibers with a packaged optoelectronic semiconductor array having a plurality of active elements mounted on a substrate within said package, comprising:

a fixture adapted to receive said uptapered optical fibers and hold them in position;

a graded index lens having a numerical aperture sufficiently large to optically access the active elements of said array;

said graded index lens having a predetermined magnification factor being positioned centrally as a function of the precise location of said active elements and rigidly secured to said substrate a fixed distance from said optoelectronic array such that a central beam between said array of said active elements and said optical fibers passes through the center of said lens;

said optical fibers being aligned with said active elements by optically coupling a central one of said uptapered single-mode optical fibers to the central light beam emanating from said optoelectronic array after said beam has been magnified by said lens; and

said uptapered optical fibers being secured to said fixture such that after alignment each of said optical fibers is positioned to be coupled with a beam of known location and size emanating from said array of active elements.

20. The package of claim **19**, wherein a ratio between the core sizes at the uptapered and downtapered ends of each optical fiber ranges from unit to ten.

21. The package of claim **19** wherein said graded index lens has a magnification factor of ten.

22. The package of claim **19** wherein said graded index lens magnifies a light beam by a factor of ten and expands the separation of light beams emanating from said active elements by a factor of ten.

23. The package of claim **19** wherein said graded index lens has a numerical aperture of 0.6.

24. The method of claim **18** wherein the number of active elements on said optoelectronic array is less that or equal to five.

25. The package of claim **19** wherein said array is a two-dimensional surface array.

26. The package of claim **25** wherein the number of active elements on said surface array is less than or equal to seventeen.

27. The package of claim **25** wherein said fixture is a mandrel.

28. The package of claim **25** wherein said active elements are arranged in a circle having the numerical aperture of said graded index lens.

29. The package of claim **19** wherein the side of said lens facing said active elements has a curved face.

30. An improved package providing for the precise, secure alignment of multiple uptapered single-mode optical fibers to a single packaged optoelectronic array device having an array of at least two light-emitting sources, said package including

a housing to enclose said light-emitting sources which convert electrical signals to optical signals,

a substrate carrier having a solderable surface within said housing, said light-emitting sources being secured to said substrate,

wherein the improvement comprises:

a portion of said substrate being adapted to receive said array of optical fibers;

a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic array;

said graded index lens being secured to said substrate of said package a fixed distance from said optoelectronic array such that the light beams from said light-emitting sources are magnified and the spacing between said beams is expanded;

said optical fibers being actively aligned with said light-emitting sources by optically coupling the thick end of one uptapered single-mode optical fiber to each light beam emanating from said opto-

electronic array after said beam has been magnified by said lens; and

said optical fibers being secured to said fiber stage of said package after alignment.

31. The improved package of claim **30**, wherein a ratio between the core sizes at the uptapered and downtapered ends of each optical fiber ranges from unity to ten.

32. The improved package of claim **30** wherein said graded index lens has a magnification factor of ten.

33. The improved package of claim **30** wherein said graded index lens magnifies a light beam by a factor of ten and expands the separation of light beams emanating from said light-emitting sources by a factor of ten.

34. The improved package of claim **30** wherein said alignment further comprises:

a fixture adapted to receive said array of uptapered optical fibers;

said graded index lens having a predetermined magnification factor being positioned centrally and rigidly secured such that a central beam between said optoelectronic array and said optical fibers passes through the center of said lens;

the position of said lens being determined by the precise location of said light-emitting sources on said optoelectronic array and the precise location of said magnified light beams from said activated light-emitting sources as magnified by said graded index lens; and

said uptapered optical fibers being secured to said fixture such that each of said optical fibers is positioned to be coupled with a beam of known location and size emanating from said activated light-emitting sources.

35. The improved package of claim **30** wherein said graded index lens has a numerical aperture of 0.6.

36. The improved package of claim **30** wherein the number of light-emitting sources on said optoelectronic array is less than or equal to five.

37. The improved package of claim **30** wherein said optoelectronic array is a two-dimensional surface emitting array.

38. The improved package of claim **37** wherein the number of light-emitting sources on said array is less than or equal to seventeen.

39. The improved package of claim **37** wherein said fixture is a mandrel.

40. The improved package of claim **37** wherein said light-emitting sources are arranged in a circle having the numerical aperture of said graded index lens.

41. The improved package of claim **30** wherein the side of said lens facing said light-emitting sources has a curved face.

42. The improved package of claim **30** wherein said graded index lens is secured to said substrate with a moderate melting point solder.

43. The improved package of claim **30** further comprising:

a photodetector monitor array and shadow mask mounted on said substrate to prevent crosstalk between monitored outputs of said optoelectronic array and to maintain constant output power.

44. The improved package of claim **30** further comprising:

a heatsink secured to said substrate carrier; and

said optoelectronic array device is die-bonded to said heatsink.

45. The improved package of claim **30**, further comprising:

a thermoelectric cooler positioned under said substrate carrier within said housing to maintain a stabilized temperature for said optoelectronic array device.

46. The improved package of claim **30** wherein said optical fibers are secured to said substrate by a room temperature curing epoxy.

47. The improved package of claim **30** further comprising a support for said optical fibers, said support being positioned at the ports of said housing through which said optical fibers extend.

48. The improved package of claim **30** further comprising:

a multi-fiber holder adapted to receive said uptapered optical fibers in fiber-receiving positions which are determined by the optoelectronic array-to-lens spacing, such that each of said uptapered optical fibers may be optically coupled to one correspondingly positioned light-emitting source through said lens;

said optical fibers in said multi-fiber holder being actively aligned with said light-emitting sources by the alignment of its central optical fiber with the corresponding central light-emitting source; and

said multi-fiber holder being secured in its aligned position with epoxy.

49. The improved package of claim **30** further comprising a cover for said housing.

* * * * *

United States Patent [19]

Boudreau et al.

[11] **Patent Number: 5,024,504**

[45] **Date of Patent: Jun. 18, 1991**

[54] **METHOD OF ALIGNING AND PACKAGING AN OPTOELECTRONIC COMPONENT WITH A SINGLE-MODE OPTICAL FIBER ARRAY**

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[73] Assignee: **GTE Laboratories Incorporated**, Waltham, Mass.

[21] Appl. No.: **439,761**

[22] Filed: **Nov. 20, 1989**

[51] **Int. Cl.⁵** **G02B 6/32**

[52] **U.S. Cl.** **350/96.18**; 350/96.20

[58] **Field of Search** 350/96.10, 96.15, 96.18, 350/96.20, 96.21, 320

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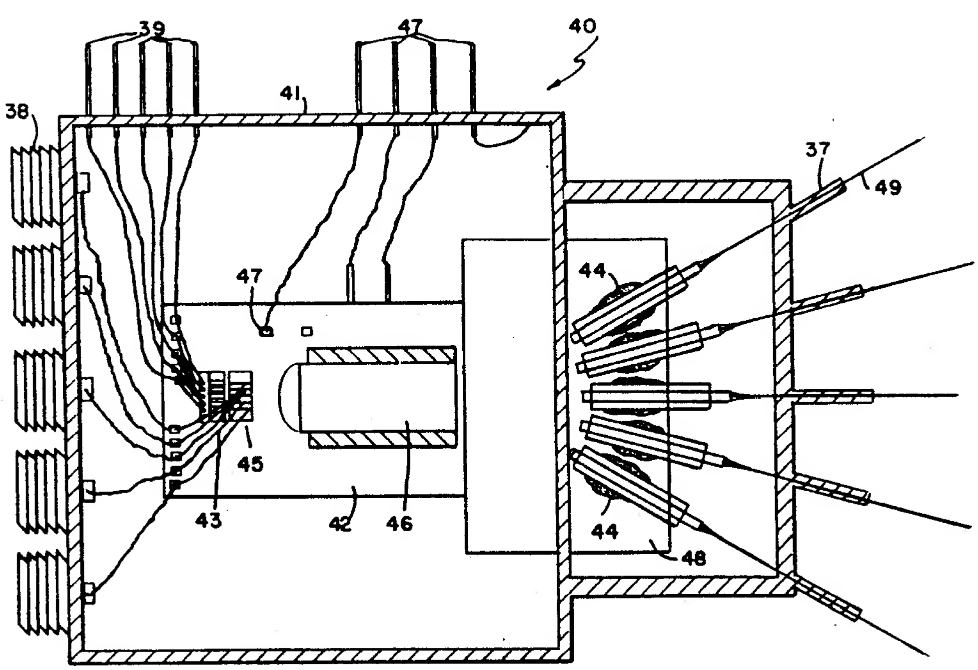
Primary Examiner—Akm Ullah

Attorney, Agent, or Firm—Victor F. Lohmann, III; James J. Cannon, Jr.

[57] **ABSTRACT**

A method for optically coupling multiple single-mode optical fibers to a single packaged optoelectronic array device uses a single graded index lens to magnify the images of the active semi-conductor elements and to expand the spacing between their light beams. These separated magnified light beams then coupled to an associated array of uptapered optical fibers. Simultaneous alignment is possible because the location of the semiconductor array beams can be known with high precision relative to the central beam in the array. A lens with known magnification is first positioned relative to the central beam. Alignment to this central beam automatically aligns other optical fibers held collectively in a fixture engineered with the geometry set by the known magnification of the lens. The coupling of single-mode optical fiber to two-dimensional semiconductor surface arrays utilizes the projected and magnified beams of the array which replicate the precise placement of the array elements. A mandrel supports the uptapered optical fibers. Simultaneous alignment of the optical fiber array is performed by first aligning the center fiber, and then rotating the mandrel until the outside fibers come into alignment.

39 Claims, 8 Drawing Sheets



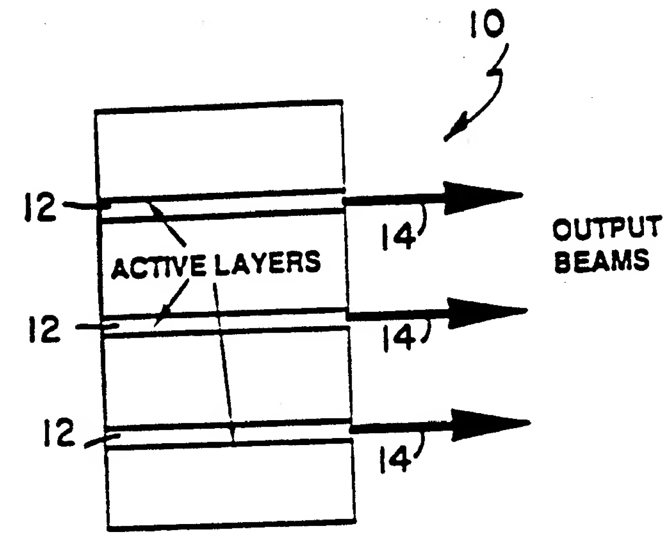


FIG. 1a

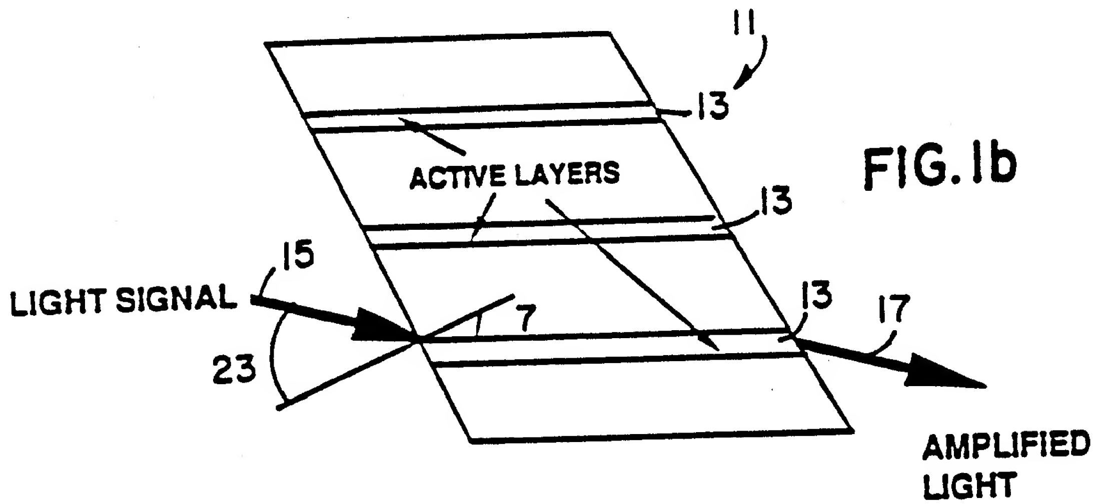


FIG. 1b

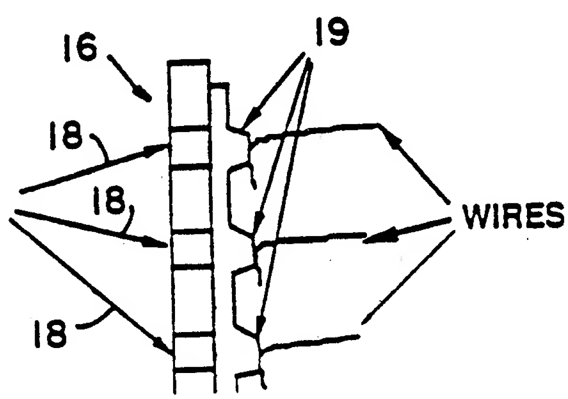


FIG. 1c

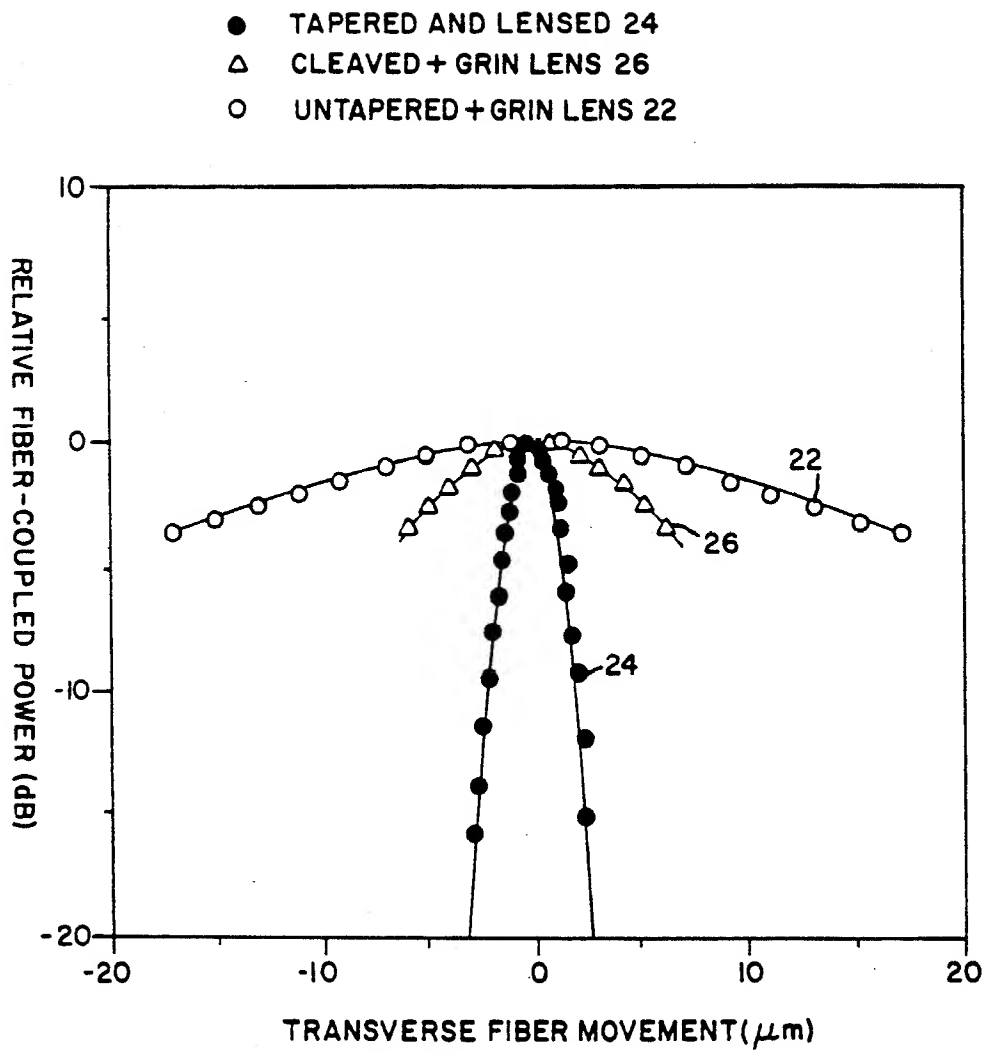

TAPERED AND LENSED 24
CLEAVED + GRIN LENS 26
UNTAPERED + GRIN LENS 22
10
0
-10
-20
RELATIVE FIBER-COUPLED POWER (dB)
-20
-10
0
10
20
TRANSVERSE FIBER MOVEMENT (μm)
22
26
24

FIG. 2

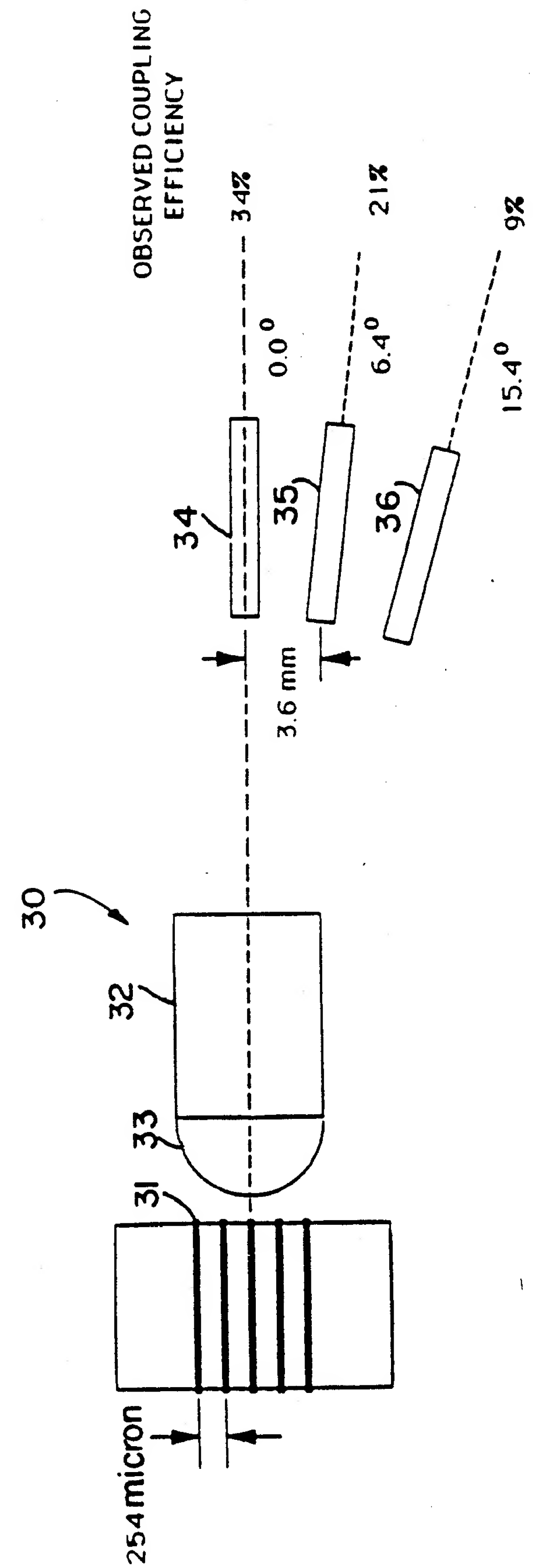

OBSERVED COUPLING EFFICIENCY
34%
21%
9%
0.0°
6.4°
15.4°
34
35
36
3.6 mm
30
32
33
31
254 micron

FIG.3

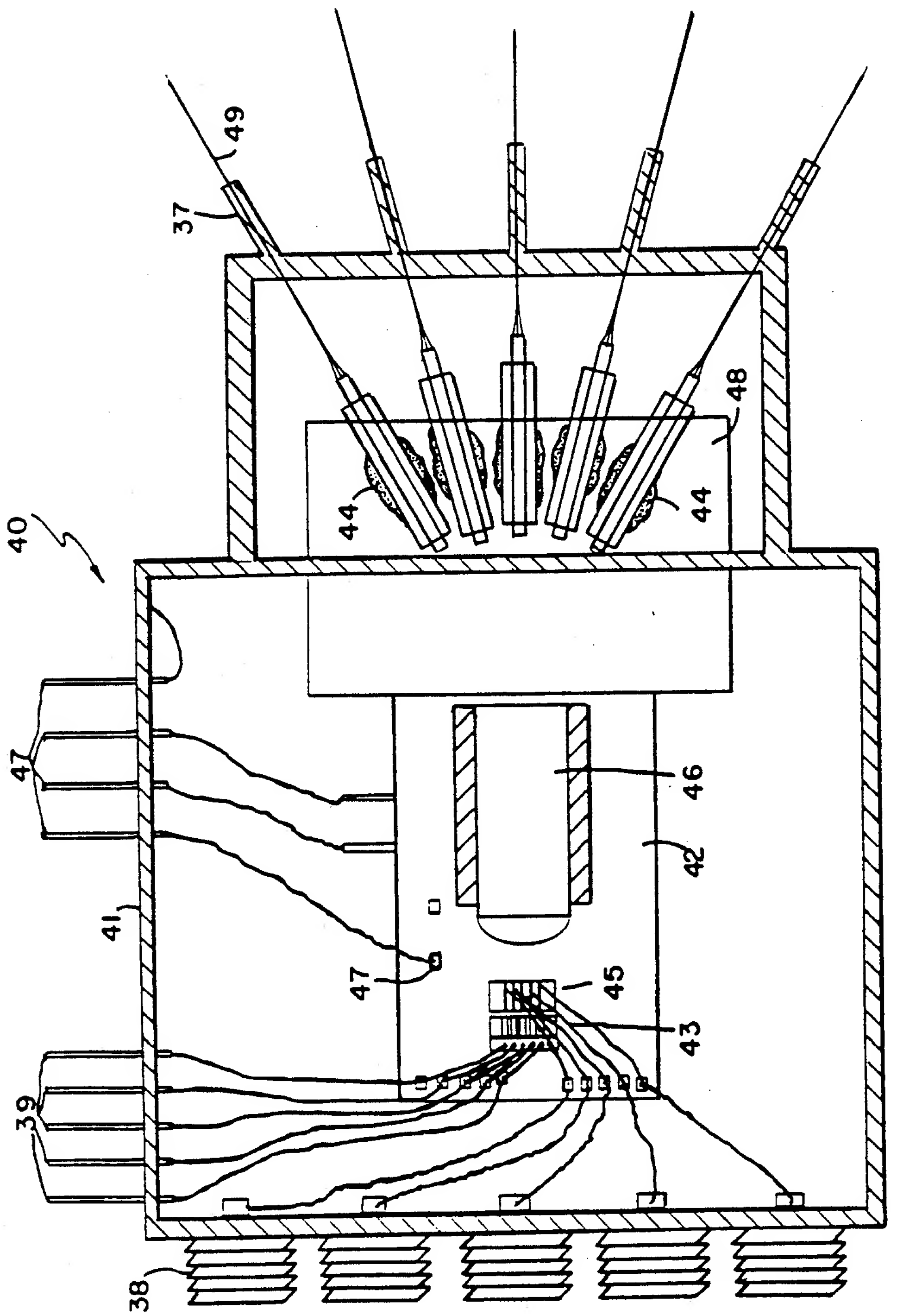


FIG. 4

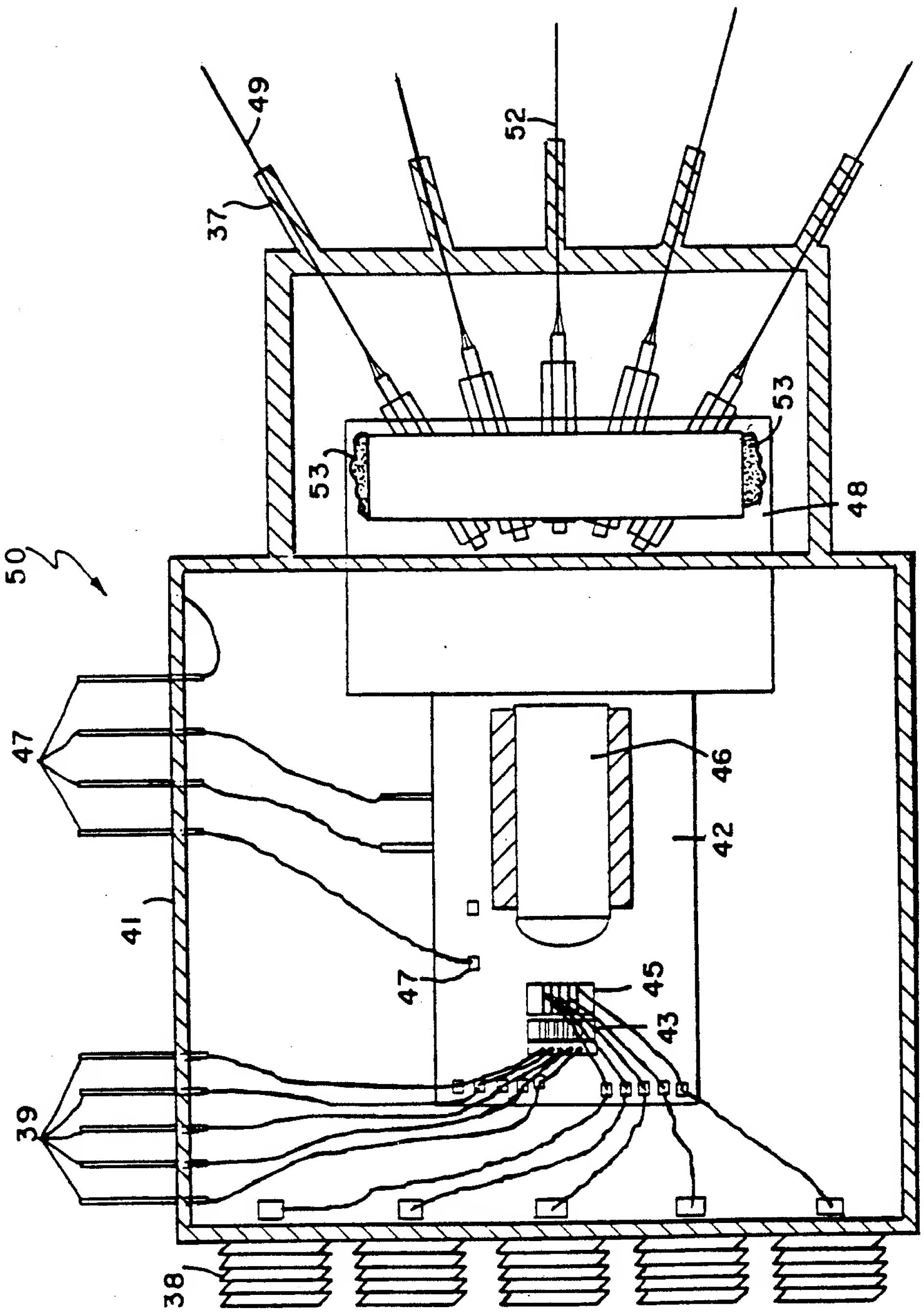


FIG. 5

FIG. 6A

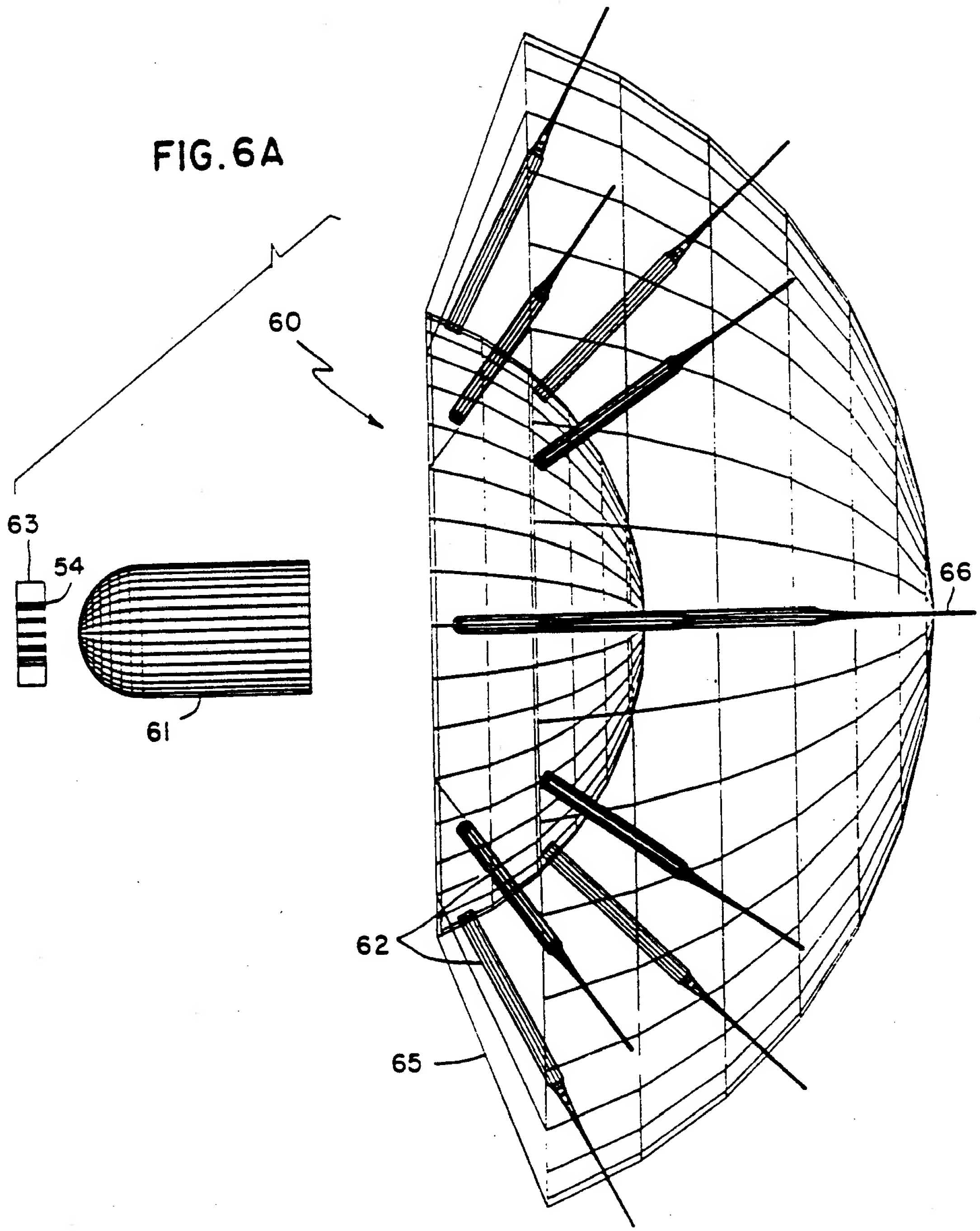


FIG.6B

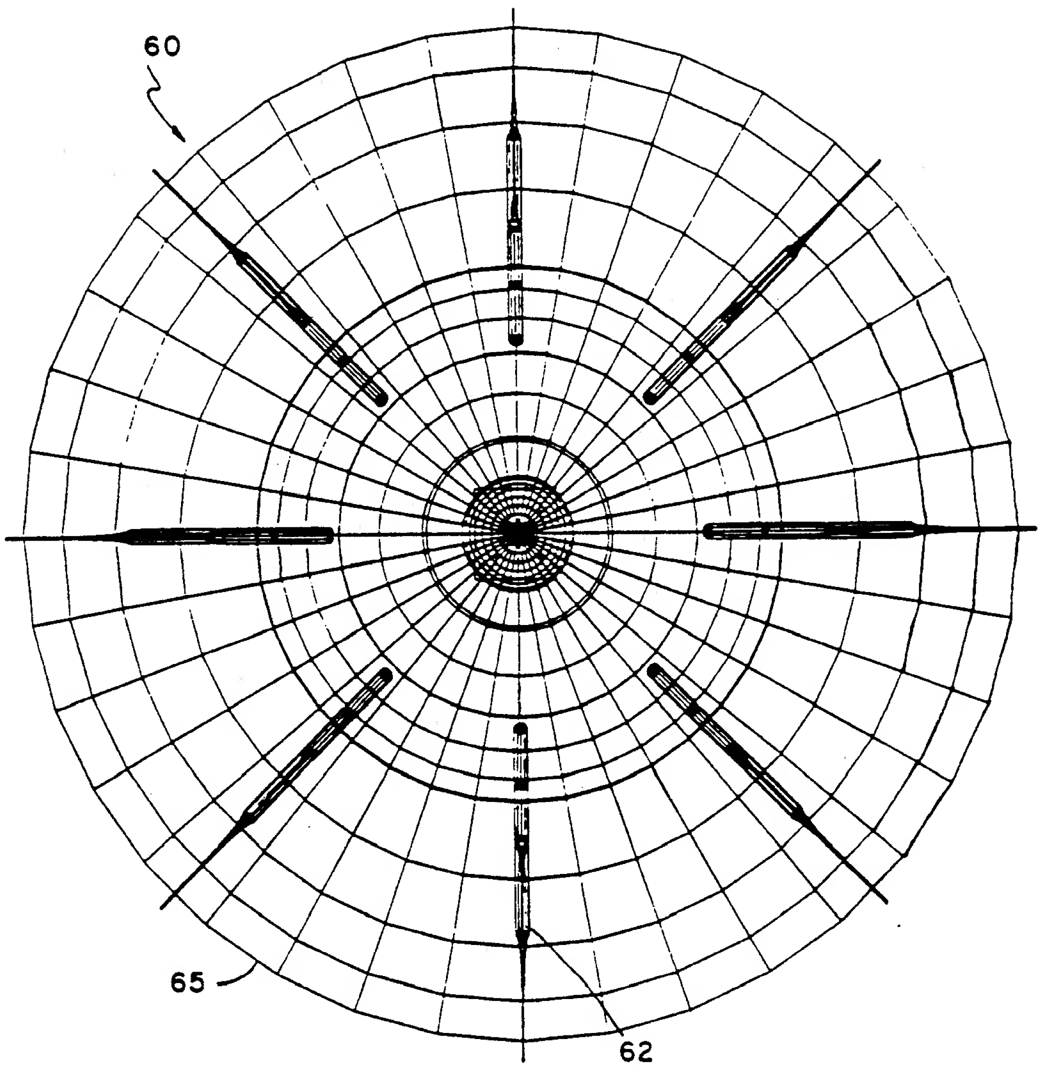
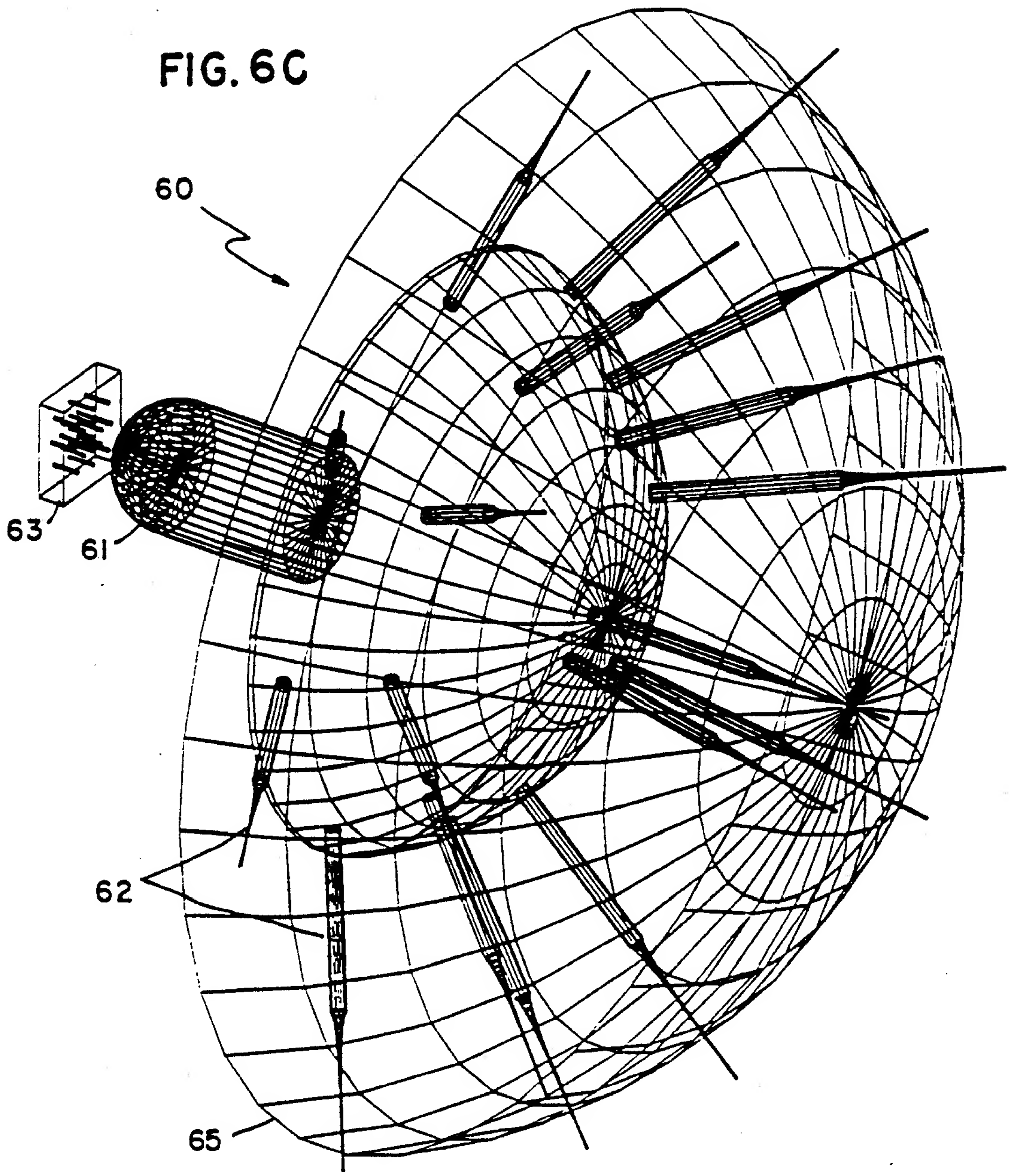


FIG. 6C



METHOD OF ALIGNING AND PACKAGING AN OPTOELECTRONIC COMPONENT WITH A SINGLE-MODE OPTICAL FIBER ARRAY

BACKGROUND OF THE INVENTION

This invention relates to packaging of optoelectronic components which generate or process signals that pass through optical fibers. In particular, it addresses the critical need for providing stable low-cost alignment of multiple single mode optical fibers to a single packaged device, such as a semiconductor array of laser amplifiers, lasers or photodetectors. Such devices have closely spaced active regions to which the optical fibers must be coupled.

An optoelectronic package is a container or housing that provides protection and support for both active and passive components contained within it. These components and their interconnection represent an optical-electrical circuit and define the function of the package. The package also includes a means of connecting the internal components with the external environment, usually as electrical feed-through and optical fiber. Our invention is concerned with the optical fiber and how it is connected to the components within the package.

To make an optical connection between an optical fiber and an optoelectronic component within a package, it is necessary to position or align the optical fiber in a way that allows efficient coupling between the optical fiber and the optoelectronic component. The precision needed for the alignment depends on the size of the light-emitting or light-receiving elements, the type of optical fiber, and any type of focusing or defocusing elements which may be present. Optical fiber transmits light through its inner core, which is much smaller than the diameter of the optical fiber. There are two classes of optical fiber presently used in packaging semiconductor devices: single-mode and multi-mode, with typical core diameters of about 10 μm and 50 μm, respectively. Many telecommunication applications use single-mode optical fiber because of the superior bandwidth arising from its reduction of mode partition noise.

The prior art for multi-fiber array alignment to a single package is predominantly concerned with the easier task of coupling large core multi-mode optical fiber to relatively large light sources and detectors. These alignments are less sensitive to position and can often be done with grooved parts and epoxy to fasten the optical fiber. This technology is acceptable for short length optical fiber links in local area networks or computers, but not for telecommunications.

Connecting single-mode optical fiber to semiconductor devices is difficult. Extremely tight tolerances, on the order of 1 μm, are needed due to the small size (about 1 μm) of the active region and the small optical fiber core. Optical fibers are usually actively aligned to the semiconductor component. This means that for the semiconductor laser, the laser is electrically biased to emit light. The optical fiber is then aligned to a position that maximizes its reception of light, a condition monitored by coupling a detector to the opposite end of the optical fiber. The manipulation of the optical fiber is usually done with a suction-tipped micromanipulator arm with piezo-electric controls having submicron positional sensitivity. Additional problems arise when more than one optical fiber needs to be coupled to a single device, since this necessarily entails either simultaneous alignment or sequential alignment to multiple optical fibers. Simultaneous alignment is a situation in which each optical fiber must be physically connected to a manipulator of some kind, the optical fibers then moved together and held in position all at the same time. Sequential alignment is the process of aligning separate optical fibers, one by one. Alignment of one optical fiber often disrupts previously aligned optical fibers such that the overall yield of the process may be low. For array alignments, the active elements may be only 150 to 300 μm apart on the semiconductor, leaving little room for holding the optical fibers, which normally have physical outside diameters (core plus cladding) of 125 μm. The optical fibers would be nearly in contact with each other when positioned for direct coupling to the active regions on the semiconductor.

Once single-mode optical fibers are aligned, they are usually fixed in their position by laser welding or soldering. It has been shown that the application of a GRIN lens with an uptapered optical fiber will increase the alignment tolerances to the extent that the more easily made epoxy attachment can be made at room temperature and without the cost of the laser welding. This advantage is present in our current invention as applied to arrays.

SUMMARY OF THE INVENTION

The principal object of the present invention is to provide a method for quick and efficient optical coupling of multiple single-mode optical fibers to an array of closely spaced active semiconductor elements.

A second object of the present invention is to provide a method for establishing optical connections that permit independent transfer of telecommunications data and information for each semiconductor element.

Another object of this invention is to provide a method that is not limited to one-dimensional arrays, such as standard edge emitters and detectors, but can also be used for two-dimensional arrays, such as surface emitters and detectors.

Still a further object of the present invention is to provide a predictable, reproducible location of the optical fibers for maximum coupling efficiency, so that an entire array of optical fibers can be simultaneously aligned, taking maximum advantage of the extreme precision of the semiconductor array dimensions.

A further object of the invention is to provide a method which offers the opportunity to introduce optical filtering of the separate beams in an array, due to the increased space between the lens and the fibers.

SUMMARY

In a first aspect of the invention, a method for precise sequential alignment of multiple single-mode optical fibers to a packaged optoelectronic component having at least two light-emitting sources begins with the selection of a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic component and securing said graded index lens on the substrate of said package a fixed distance from said optoelectronic component. Uptapered optical fibers are sequentially aligned with said light source by optically coupling one uptapered single-mode optical fiber to each light beam emanating from said optoelectronic component after said beam has been magnified by said lens and then securing said optical fibers to said package after alignment.

In a second aspect of the invention, a method for precise simultaneous alignment of multiple single-mode optical fibers to a single packaged optoelectronic array device having at least two light-emitting sources begins with the selection of a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic array and securing said graded index lens on the substrate of said package a fixed distance from said optoelectronic array such that the light beams from said light-emitting sources are magnified and the spacing between said beams is expanded. Then a plurality of uptapered optical fibers, all held in a single holder having the fibers in predetermined locations, are aligned with said light sources by optically coupling the thick end of one centrally disposed uptapered single-mode optical fiber to its associated light beam emanating from said optoelectronic array, automatically and simultaneously aligning any other uptapered fibers after said beam has been magnified by said lens and securing said optical fibers to said package after alignment.

In a third aspect of the invention, a method for simultaneous, precise alignment of an array of multiple single-mode optical fibers to a single packaged optoelectronic array device having a two dimensional array, such as a surface array, of at least two light-emitting sources begins with the selection of a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting source of said optoelectronic array and securing said graded index lens on the substrate of said package a fixed distance from said optoelectronic array such that the light beams from said light-emitting sources are magnified and the spacing between said beams is expanded. Then the array of uptapered optical fibers is positioned and secured in a fixture such that the spacing of the thick ends of said uptapered optical fibers matches the spacing of said light beams emanating from said array after magnification and separation by said lens. The array of uptapered optical fibers in said fixture is then actively aligned with said light sources by optically coupling the thick end of one uptapered single-mode optical fiber centrally positioned in said fixture to that light beam emanating from a central light source of said optoelectronic array after said beam has been magnified by said lens, followed by rotation of said fixture until a second uptapered single-mode fiber is aligned simultaneously, thereby aligning all of said fibers with said light sources and said fixture is secured to said package after alignment.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1***a* is a schematic top view of an array of three semiconductor lasers;

FIG. **1***b* is a schematic top view of an array of three semiconductor laser amplifiers;

FIG. **1***c* is a schematic side view of an array of three semiconductor optical detectors;

FIG. **2** is a graph showing the transverse sensitivities of various single-mode optical fiber couplings to a semiconductor laser;

FIG. **3** is a diagrammatic view of a first embodiment of the method of the invention illustrating the use of a GRIN lens to couple an array of uptapered optical fibers to a semiconductor laser array;

FIG. **4** is a top cut-away view of a first embodiment of an optoelectronic package embodying the method illustrated in FIG. **4**;

FIG. **5** is a top cut-away view of a second embodiment of an optoelectronic package, similar to that of FIG. **4**, but further including a multi-fiber holder; and

FIGS. **6***a*, **6***b*, and **6***c* are side, end and perspective views respectively of an embodiment of an optoelectronic package in which uptapered optical fibers are coupled through a lens to a seventeen-element, two-dimensional semiconductor surface array.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention pertains to a method for quick and efficient optical coupling of multiple single-mode optical fibers to an array of closely spaced active semiconductor elements, and to optoelectronic packages incorporating the method. Examples of semiconductor devices which require multiple optical fibers set in an array are shown in FIGS. **1***a*, **1***b* and **1***c*. FIG. **1***a* shows an array **10** of semiconductor lasers **12**, used as light sources for such purposes as parallel processing. An optical fiber must be coupled to each lasing output beam **14**. FIG. **1***b* shows an array **11** of optical amplifiers **13**, which receive light at one end and output the amplified light at the other end. One array of optical fibers **15** must couple the light signals into the optical amplifiers, and another array of optical fibers **17** must couple the amplified output. FIG. **1***c* shows an array **16** of detectors **19**. One array **18** of optical fibers must couple the light signals into these detectors **19**.

FIG. **2** shows coupling performance, that is, the effect on relative fiber-coupled power and dB of transverse fiber movement, between a single-mode optical fiber and a high speed laser, a typical telecommunications component. For conventional tapered and lensed optical fibers, shown on line **24**, the position sensitivity can be as little as 1 μm, a size much smaller than the parts themselves. Prior art shows alignment methods and packages based on these alignment methods for one single-mode optical fiber per package. FIG. **2** also shows the use of an uptapered optical fiber and a graded index (GRIN) lens, line **22**. This uptapered fiber system has the advantage of relaxing the lateral positional tolerances of the optical fiber at the expense of tightening the angular tolerances. FIG. **2** also shows the third case where a GRIN lens is used with a standard cleaved optical fiber, line **26**. This is an intermediate case of positional sensitivity, but is considered unfavorable because it is not suited to work with as much magnification as is the uptapered fiber. With all methods, problems are compounded when more than one single-mode optical fiber must be aligned to the same package in an array. By reducing the positional sensitivity, it is possible to achieve the necessary yield improvement required for doing array alignments.

The method of this invention uses a lens, with a sufficient numerical aperture and magnification, in conjunction with uptapered single-mode optical fiber. The technique takes advantage of the relaxed mechanical tolerance and increased fiber-to-fiber spacing arising from the magnification provided by the lens and the larger cored uptapered fiber optics. Such optical connections then permit independent transfer of telecommunications data and information for each semiconductor element.

Specifically, this invention provides a new method for optically coupling multiple single-mode optical fibers to a single packaged optoelectronic array device using a single lens with the array of semiconductor elements in order to magnify the images of the various

active elements to expand the spacing between them as well as their size. These separate images are then coupled to an array of uptapered optical fibers. This magnification greatly facilitates mechanical alignment and coupling of the semiconductor elements to the associated array of optical fibers by relaxing mechanical tolerances associated with the positions of the rays of light coming from the multiple lasers. It also separates the positions of the rays sufficiently to allow space for mechanical fixturing to hold the separate optical fibers to receive the light.

Uptapered optical fibers are used because the effect of magnification not only increases the spacing between the separate rays of light but also increases the size of the separate beams or spots. These beams are best collected on the thick end of the uptapered fiber, where the size of the optical fiber best matches the size of the separate beams. For example, a typical uptapered optical fiber may have a core that is 10 times larger on its thick end than the single mode fiber it tapers down to. This optical fiber is used with a lens that magnifies everything ten fold, both the spot size of the beam as well as the spacing between beams. This effect facilitates the alignment when assembling an optoelectronic package, since the magnification typically results in a spacing of about 3 mm between separate light beams.

This description of the preferred embodiments also applies to the case of an array of detectors, in which case the light path is simply in the reverse direction, passing from the optical fiber to the semiconductor.

Simultaneous alignment is possible with this system because the location of the semiconductor array beams can be known with high precision relative to the central beam in the array. This is because the semiconductor elements are usually patterned on the semiconductor with photolithography to a high level of precision, about 1 μm, and the lens projects a precise image of this pattern towards the fibers. If a lens with known magnification is first positioned rigidly in a central specified location, then the location of the other projected beams are known. Alignment to this central beam automatically would align other optical fibers held collectively in a fixture engineered with the geometry set by the known magnification determined by the lens. Tolerance errors are also greatly reduced if only a single lens is used, eliminating errors incurred from alignment of multiple lenses to each other.

One limitation of the invention that must be considered is the issue of numerical aperture (N.A.) of the lens. This is analogous to field of view through a microscope or a pair of binoculars. The numerical aperture of the lens is defined as:

$$N.A.=n_o \sin a$$

where a=lens acceptance angle.
and n_o=index of refraction of the lens.

This limits the number of semiconductor elements arranged in a line that can be accessed optically. A lens with the largest possible numerical aperture should be chosen. A good value for the numerical aperture is about 0.6, and all our experimentation was conducted with a lens having this numerical aperture. Using this lens we were able to easily couple to an in-line **5** element array.

One special feature of our invention is that the effect of the N. A. limitation can be eliminated or reduced when used in conjunction with a surface emitting array since the field of view is two-dimensional. Presently, no schemes exist for coupling single mode optical fiber to semiconductor surface arrays. However, this method is valuable in making it possible by relaxing positional tolerances. Since the system works well with a five element in-line array, it follows, that it works for a seventeen-element surface array having elements arranged within an numerical aperture limited circle on the semiconductor. The projected and magnified image of the surface array replicates the high precision of the placement of the array elements, facilitating the fabrication of a support structure or mandrel which supports the uptapered optical fibers. Simultaneous alignment to all optical fibers is performed by first aligning the center fiber, and then rotating the mandrel to align the rotational orientation.

FIRST EMBODIMENT

The first embodiment of this invention is the method of using a GRIN lens to couple an array of uptapered optical fibers to a semiconductor laser array. This is shown in FIG. **3**. The semiconductor laser array **30** is a single solid-state microelectronic chip with five separate laser elements **31** on it. The GRIN lens **32** used is a SELFOC pch 1.8-0.22 Micro Lens (SML). It has a physical diameter of 1.8 mm and an overall length of 3.3 mm. A curvature **33** is present on the end of the lens closest to the laser array in order to reduce distortions and increase the numerical aperture to 0.6. The lens **32** is centered on the laser array **30** and is located at a distance of about 0.37 mm from the laser array **30**. A first uptapered optical fiber **34** is located about 15 mm away from the back of the lens **32**. The spacing between lasers **31** in the array **30** is about 250 μm, while separation between uptapered optical fibers, **34**, **35**, **36** as a result of the magnification is about 3 mm. The separate light beams emerging from the lens arrive at the uptapered optical fibers **34**, **35**, **36** at different angles depending on the magnification and the displacement of the separate light sources from the centerline of the lens **32**. For the five-element case shown, the outside beams arrive at about 15 degrees as compared to 0 degrees for the central beam.

When optically aligning this system, it is important to first rigidly fix the location of the GRIN lens **32** with respect to the laser array **30**. This is done with a moderate melting point solder rather than a low melting point solder to reduce creep of the parts. The magnification is highly dependent on the array-to-lens distance. For example this lens produces magnifications of about 34, 9.7, and 4 for laser-to- lens distances of about 0.3, 0.4, and 0.6 mm respectively. The magnification is selected depending on the predetermined spacing desired between separate uptapered optical fibers **34**, **35**, **36**, or what would best match the spot size of the magnified beam and the uptapered optical fiber cores. In this embodiment, a magnification of about 10 was used.

Alignment of the uptapered optical fibers **34**, **35**, **36** to the beam should be done to a precision of about 0.5 degrees of arc. Since the uptapered optical fibers have a fairly long, narrow and rigid geometry, this tolerance is easy to achieve. Also, as shown in FIG. **2**, the uptapered optical fiber has a more relaxed transverse positional tolerance compared to conventional fiber. In our test of this embodiment, the optical fibers **34**, **35**, **36** were actively aligned using a micromanipulator while the laser array **30** was operating. The manipulator was capable of

controlling the optical fiber position to a transverse tolerance of about 5 μm.

SECOND EMBODIMENT

The second embodiment of this invention is a package apparatus employing the method described in the first embodiment. This package, for use with a five-element laser array, is shown in FIG. **4**. A metal housing **41**, indicated by the dotted grey border in the diagram, encloses the necessary components that convert input electrical signals **38** to optical signals. A carrier **42** having a surface that is readily solderable, such as gold plated copper or brass, is used to support the components. The photodetector monitor array **43** and its associated shadow mask to prevent cross-talk between monitored array outputs **39** is optional. Its function is to keep the laser output power constant but it may not be necessary depending on the lasers or the application.

As in common practice, the semiconductor array **45** is first diebonded to an efficient thermally conductive heatsink such as diamond or boron nitride. The unit is then located on the carrier **42** by soldering to either a pedestal or a reference mark. For our package, this can be done to an accuracy of about 15 μm. The GRIN lens **46** is then located on the same carrier **42** with respect to the laser **45** using a mechanical stop on the carrier **42**, and soldered in place with a moderate melting point solder such as 62/36/2 SnPbAg eutectic which melts at 179 degrees C.

The carrier assembly is completed by adding the usual thermistor **47** and internal wirebonds. Finally, the carrier is soldered to the top of a thermoelectric cooler (TEC) (not shown) which is located within the package housing. When the package is in operation, the TEC in conjunction with the thermistor is used to stabilize the operating temperature of the semiconductor **45** to maintain constant output power, a common practice. Wirebonding is performed to connect components on the carrier to the output and input electrical pins.

As shown in FIG. **4**, part of the carrier **42** includes a section called the fiber stage **48**. This is the part to which the uptapered optical fibers **49** attach. The fiber stage **48** is best as an integral part of the carrier **42** to reduce small movements of the optical fiber **49** relative to the lens **46**.

The optical fiber alignment is done actively, as described earlier for single element semiconductors, except that the alignments are done sequentially and fastened in position with a room temperature curing epoxy to prevent disturbance of previously aligned optical fibers. The uptapered fiber optics relaxes the tight transverse tolerances sufficiently to allow for an epoxy fastening, as discussed earlier. Each alignment is done separately using the vacuum tip micromanipulator.

The package is completed by sealing a lid on it with epoxy and providing additional support for the optical fibers exiting the package trough the fiber ports. The package is then tested and ready for delivery.

THIRD EMBODIMENT

The third embodiment is the package apparatus **50** and method for doing a simultaneous alignment of the array fibers. This is shown in FIG. **5**. The 50 package and its assembly is basically the same as described in the second embodiment except that all the optical fibers are previously mounted in a multi-fiber holder **51**. The geometry of the holder **51** is predetermined based on the laser array-to-lens spacing. The multi-fiber holder **51** is then aligned to the center laser beam by actively aligning the center optical fiber **52** only. Most of the error associated with the alignment of the other fibers is taken up in this first alignment. The central optical fiber alignment automatically positions the alignment of the other optical fibers because of the photolithographic precision of the active laser elements on the chip as discussed before. The holder **51** is then epoxied **52** in position as it if were a single optical fiber and the package is completed as described earlier. This system sacrifices some precision in exactly locating each optical fiber in exchange for a process that requires less time to complete all alignments.

FOURTH EMBODIMENT

The fourth embodiment is the method of using the graded index lens **61** with uptapered optical fibers **62** to couple to elements **64** of a two-dimensional surface array **63**. This is shown in FIGS. *6a*, *6b* and *6c*. Since the numerical aperture of the lens **61** accepts light from a two-dimensional surface in the same way as it does from a line of active elements, it follows that the method will work to the same degree of precision and tolerance for other cases. As shown in the figure, light emitted from as many as seventeen elements **64** can be transmitted through the lens **61** to the optical fibers **62**. In practice, it is recommended that the optical fibers **62** be held in a support mandrel **65** as shown schematically in the FIGS. *6a*–*6c*. This allows for the use of the basic simultaneous alignment scheme as described above by first doing an active alignment to the center optical fiber **66** and then rotating the mandrel until the outside fibers come into alignment. The entire mandrel **65** can be then potted into position with epoxy.

VARIATIONS

The major variation possible for our invention is the use of lenses other than a (graded index) lens. It is reasonable that a convex, planer-convex, or other partially convex lens may be substituted to achieve a similar magnification effect. It is also possible to use cleaved optical fibers rather than uptapered optical fibers and still get a functional package but we prefer the uptapered optical fibers since they are used with more magnification. The system will work for local area networks (LAN) as well as computers, video and telecommunications. Finally, it should be remembered that our invention applies to any semiconductor array of active elements that needs coupling to a set of optical fibers and is not limited to laser arrays described in the embodiments.

This invention offers substantial advantages. First, it is not limited to one-dimensional arrays, such as standard edge emitters and detectors but can also be used for two-dimensional arrays, such as surface emitters and detectors. Secondly, the technique provides a predictable, reproducible location of the optical fibers for maximum coupling efficiency, so that the entire array can be simultaneously aligned. This takes maximum advantage of the extreme precision of the semiconductor array dimensions. Thirdly, this method offers the opportunity to introduce optical filtering of the separate beams in an array, due to the increased space between the lens and the optical fibers. Finally, packages for optoelectronic components incorporating this method are feasible.

We claim:

1. A method for the precise alignment of multiple uptapered single-mode optical fibers to a single pack-

aged optoelectronic array device having at least two light-emitting sources, comprising the steps of:

selecting a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic array for optically coupling each uptapered optical fiber to a respective light emitting source of said array through said lens;

securing said graded index lens on a substrate of said package a fixed distance from said optoelectronic array such that the light beams from said light-emitting sources are magnified and the spacing between said beams is expanded;

sequentially aligning said optical fibers with said light-emitting sources by optically coupling the thick end of each of said uptapered single-mode optical fiber to a respective light beam emanating from said optoelectronic array after said beam has been magnified by said lens; and

securing said optical fibers to said package after alignment.

2. The method of claim **1**, wherein a ratio between the core sizes at the uptapered and downtapered ends of each optical fiber ranges from unity to ten.

3. The method of claim **1** wherein said graded index lens has a magnification factor of ten.

4. The method of claim **1** wherein said graded index lens magnifies a light beam by a factor of ten and expands the separation of light beams emanating from said light-emitting sources by a factor of ten.

5. The method of claim **1** wherein said graded index lens has a numerical aperture of 0.6.

6. The method of claim **1** wherein the side of said lens facing said light-emitting sources has a curved face.

7. The method of claim **1** wherein the number of light-emitting sources on said optoelectronic array device is less than or equal to five.

8. The method of claim **1** wherein the step of aligning said optical fibers with said light-emitting sources further comprises the steps of:

determining the precise location of said light-emitting sources on said optoelectronic array device;

positioning centrally and rigidly securing said graded index lens having a predetermined magnification factor such that a central light beam from said optoelectronic array passes through said the center of said lens;

determining the precise location of said magnified light beams from said activated light-emitting sources as magnified by said rigidly positioned graded index lens having a known magnification factor; and

securing said uptapered optical fibers to a fixture such that each of said optical fibers is positioned to be coupled with a light beam of known location and size emanating from said activated optoelectronic array.

9. The method of claim **8** wherein said optoelectronic array device is a two-dimensional.

10. The method of claim **9** wherein said two-dimensional array is a surface emitting array.

11. The method of claim **8** wherein the number of light sources on said array is less than or equal to seventeen.

12. The method of claim **8** wherein said fixture is a mandrel.

13. The method of claim **8** wherein said light-emitting sources are arranged in a circle having the numerical aperture of said graded index lens.

14. The method of claim **8** further comprising the step of rotating said fixture until all of said optical fibers are optically coupled to all of said light beams.

15. A method for simultaneous precise alignment of multiple uptapered single-mode optical fibers to a single packaged optoelectronic array device having an array of at least two light-emitting sources, comprising the steps of:

selecting a graded index lens having a numerical aperture sufficiently large to optically access the light-emitting sources of said optoelectronic array device;

securing said graded index lens on a substrate of said package a fixed distance from said optoelectronic array device such that the light beams from said light-emitting sources are magnified and the spacing between said beams is expanded;

positioning and securing a plurality of uptapered optical fibers in a fixture such that the spacing of the thick ends of said uptapered optical fibers matches the spacing of said light beams emanating from said array after magnification and separation by said lens;

simultaneously aligning all of said optical fibers in said fixture with said light-emitting sources by optically coupling the thick end of one uptapered single-mode optical fiber centrally positioned in said fixture to that light beam emanating from a central light-emitting source of said optoelectronic array after said beam has been magnified by said lens, thereby aligning all of said optical fibers with said light sources; and

securing said fixture to said package after alignment.

16. The method of claim **15** wherein a ratio between the core sizes at the uptapered and downtapered ends of each optical fiber ranges from unity to ten.

17. The method of claim **15** wherein said graded index lens has a magnification factor of ten.

18. The method of claim **15** wherein said graded index lens magnifies a light beam by a factor of ten and expands the separation of light beams emanating from said light-emitting sources by a factor of ten.

19. The method of claim **15** wherein said graded index lens has a numerical aperture of 0.6.

20. The method of claim **15** wherein the side of said lens facing said light-emitting sources has a curved face.

21. The method of claim **15** wherein the number of light-emitting sources on said optoelectronic array device is less that or equal to five.

22. The method of claim **15** wherein the step of securing said graded index lens further comprises the steps of:

determining the precise location of said light-emitting sources on said optoelectronic array device; and

positioning centrally and rigidly securing said graded index lens having a predetermined magnification factor such that a central light beam from said optoelectronic array device passes through said the center of said lens.

23. The method of claim **15** wherein the step of simultaneously aligning all of said optical fibers further comprises the steps of:

determining the precise location of said magnified light beams from said light-emitting sources as

magnified by said rigidly positioned graded index lens having a known magnification factor; and

securing said uptapered optical fibers to a fixture such that each of said optical fibers is positioned to be coupled with a light beam of known location and size emanating from said array.

24. The method of claim **23** wherein said array of light-emitting sources is a two-dimensional array.

25. The method of claim **24** wherein said two-dimensional array is a surface emitting array.

26. The method of claim **24** wherein that number of light-emitting sources on said array is less than or equal to seventeen.

27. The method of claim **24** wherein said fixture is a mandrel.

28. The method of claim **24** wherein said light-emitting sources are arranged in a circle having the numerical aperture of said graded index lens.

29. The method of claim **24** further comprising the step of rotating said fixture until a second uptapered single-mode optical fiber is aligned simultaneously, thereby optically coupling all of said optical fibers to all of said light beams.

30. A method for the precise alignment of an array of uptapered multiple single-mode optical fibers to a two-dimensional semiconductor laser array in a packaged optoelectronic component, said array having at least two light-emitting sources, comprising the steps of:

predetermining the spacing required between said optical fibers for optimal coupling to said light-emitting sources;

positioning and centering a graded index lens at a distance from said two-dimensional array, said lens having a numerical aperture such that said lens can access optically all light-emitting sources of said array and magnify a light beam emanating from said light-emitting sources and such that a central light beam from said array passes through the center of said lens;

securing said lens to a substrate of said component with a moderate melting point solder at a calculated fixed array-to-lens distance which is a function of the magnification desired;

an array of uptapered optical fibers positioned at a distance from said lens, the central uptapered fiber of said array being positioned for optical coupling to a light beam emanating from the central light-emitting source of said laser array;

determining the precise location of said magnified light beams from said light-emitting sources as magnified by said rigidly positioned graded index lens having a known magnification factor; and

securing said uptapered optical fibers to a fixture such that each of said uptapered optical fibers is positioned to be optically coupled with a light beam of known location and size emanating from said optoelectronic component;

actively aligning the central uptapered optical fiber by coupling the thick end of said fiber to the central beam emanating through said lens;

rotating said fixture until a second uptapered single-mode optical fiber is aligned simultaneously, thereby optically coupling all of said optical fibers to all of said light beams; and

securing said fixture to said package after alignment.

31. The method of claim **30** wherein a ratio between the core sizes at the uptapered and downtapered ends of each optical fiber ranges from unity to ten.

32. The method of claim **30** wherein said graded index lens has a magnification factor of ten.

33. The method of claim **30** wherein said graded index lens magnifies a light beam by a factor of ten and expands the separation of light beams emanating from said light-emitting sources by a factor of ten.

34. The method of claim **30** wherein said graded index lens has a numerical aperture of 0.6.

35. The method of claim **30** wherein the side of said lens facing said light-emitting sources has a curved face.

36. The method of claim **30** wherein said light-emitting sources comprise a two-dimensional surface emitting array.

37. The method of claim **30** wherein the number of light-emitting sources on said two-dimensional array is less than or equal to seventeen.

38. The method of claim **30** wherein said fixture is a mandrel.

39. The method of claim **30** wherein said light-emitting sources are arranged in a circle having the numerical aperture of said graded index lens.

* * * * *

US006334019B1

(12) **United States Patent**
Birks et al.

(10) **Patent No.: US 6,334,019 B1**
(45) **Date of Patent: Dec. 25, 2001**

(54) **SINGLE MODE OPTICAL FIBER**

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(73) Assignee: **The Secretary of State for Defence in Her Britannic Majesty's Government of the United Kingdom of Great Britain and Northern Ireland**, Farnborough (GB)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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PCT Pub. Date: **Jan. 7, 1999**

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(51) **Int. Cl.**[7] **G02B 6/02**

(52) **U.S. Cl.** **385/125**; 385/127

(58) **Field of Search** 385/125, 123, 385/126, 127, 147, 124

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Primary Examiner—Cassandra Spyrou
Assistant Examiner—Euncha Cherry
(74) *Attorney, Agent, or Firm*—Nixon & Vanderhye P.C.

(57) **ABSTRACT**

A large core photonic crystal fiber for transmitting radiation having a core comprising a substantially transparent core material and having a core diameter of at least 5 μ. The fiber also comprises a cladding region surrounding the length of core material, wherein the cladding region comprises a first substantially transparent cladding material, having a first refractive index, and wherein the first substantially transparent cladding material has embedded along its length a substantially periodic array of holes, wherein the holes are filled with a second cladding material having a second refractive index less than the first refractive index, such that radiation input to the optical fiber is transmitted along the length of the core material in a single mode of propagation. In a preferred embodiment, the core diameter may be at least 20 μ, and may be as large as 50 μ. The fiber is capable of transmitting higher power radiation than conventional fibres, whilst maintaining propagation in a single mode. The core material may be doped with a material capable of providing amplification under the action of pump radiation input to the fiber. The invention also relates to a fiber amplifier and a fiber laser comprising a doped large core photonic crystal fiber. The fiber may also be used in a system for transmitting radiation comprising a plurality of lengths of large core photonic crystal fiber, separated by large core photonic crystal fiber amplifiers, such that the power of radiation transmitted through the system is maintained above a predetermined threshold power.

31 Claims, 6 Drawing Sheets

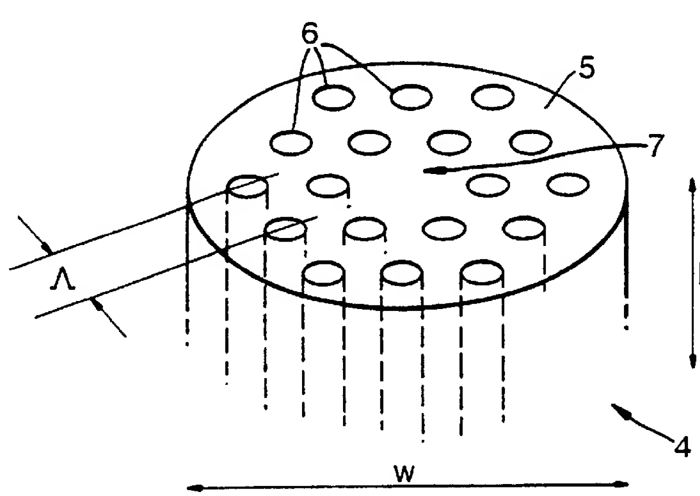


Fig.1.

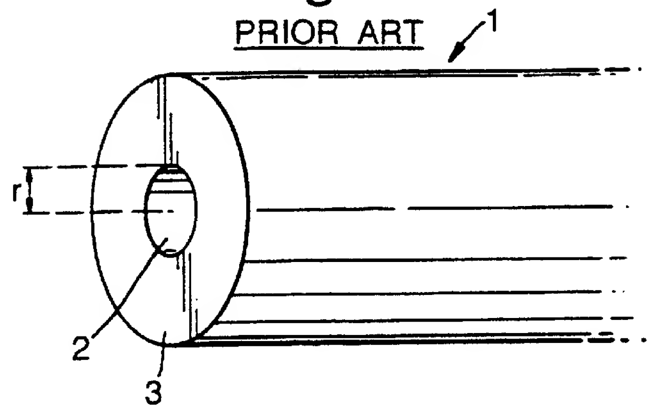


Fig.2(a).

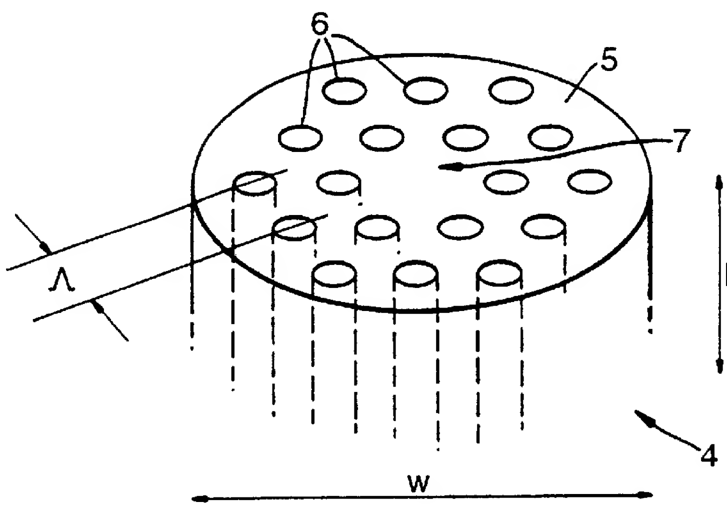


Fig.2(b).

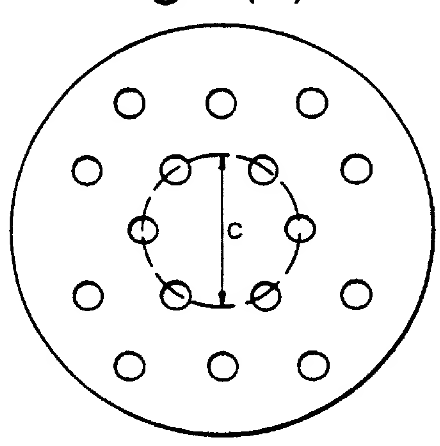


Fig.3(a).

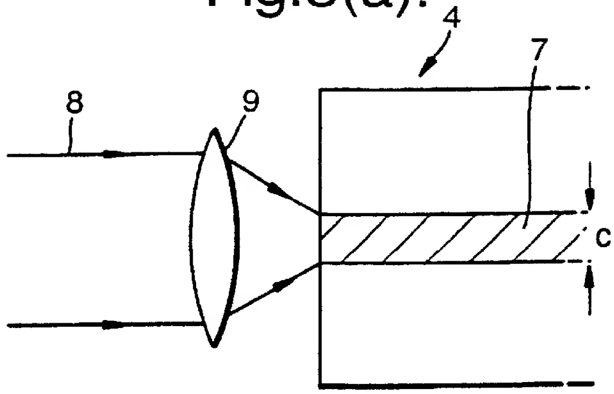


Fig.3(b).

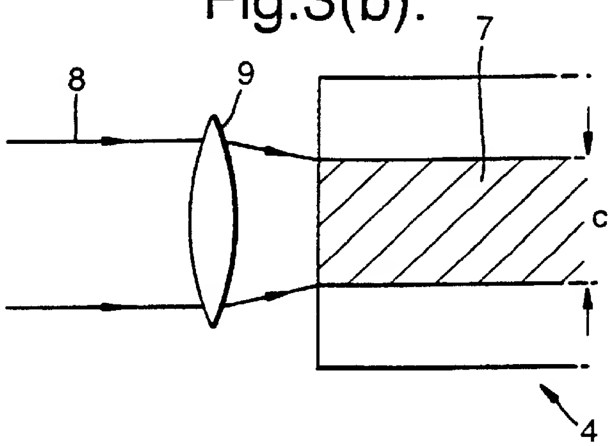


Fig.4.

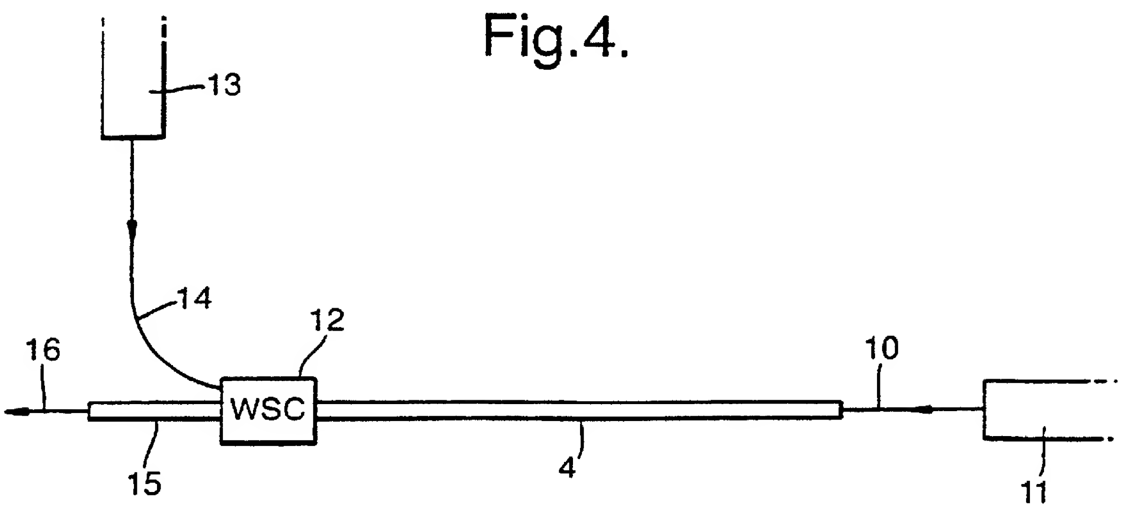


Fig.5.

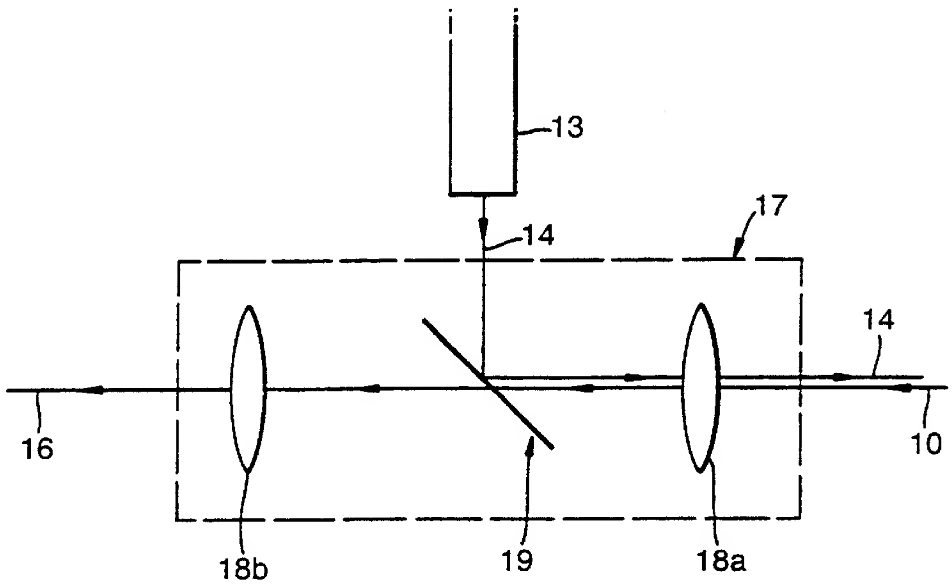


Fig.6.

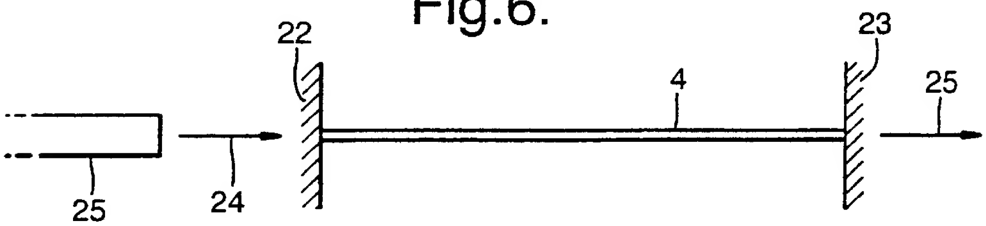


Fig.7.

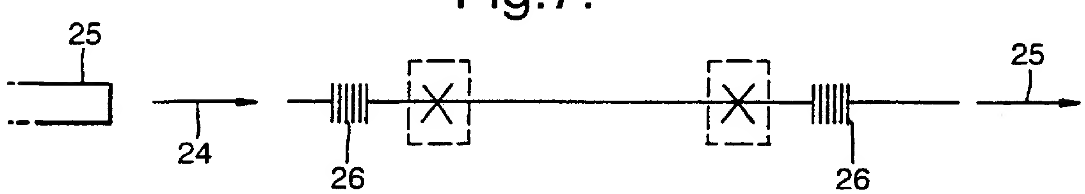


Fig.8(a).

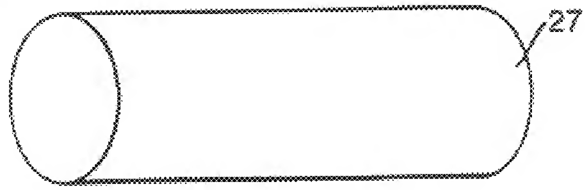


Fig.8(b).

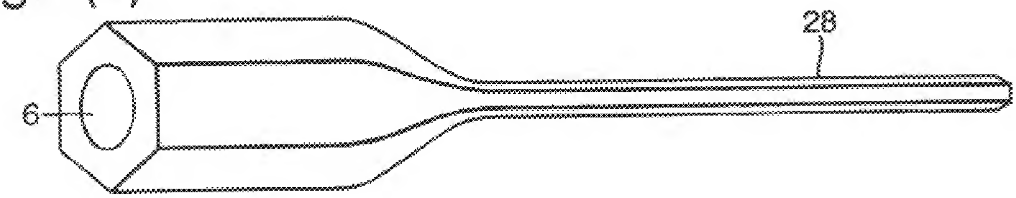


Fig.8(c).

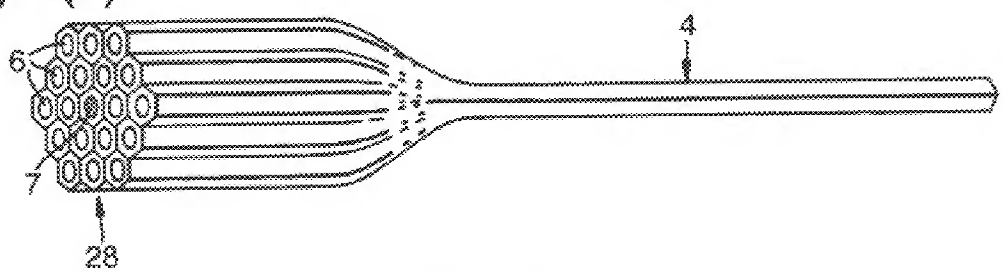


Fig.9.

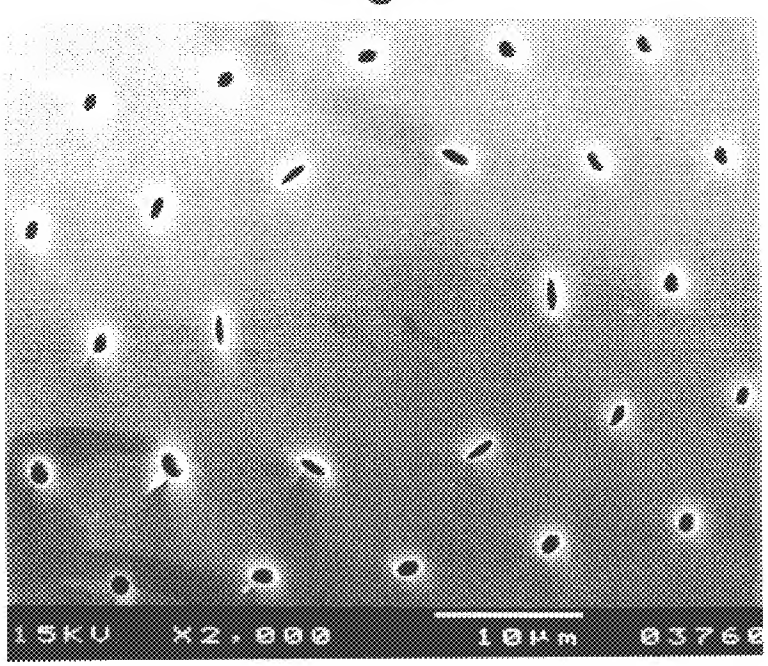


Fig.10.

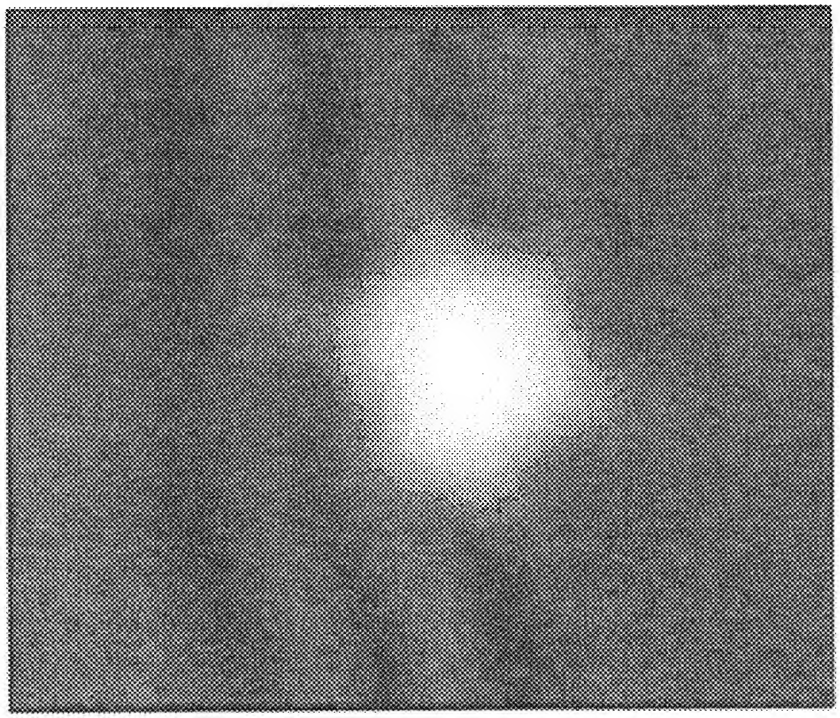
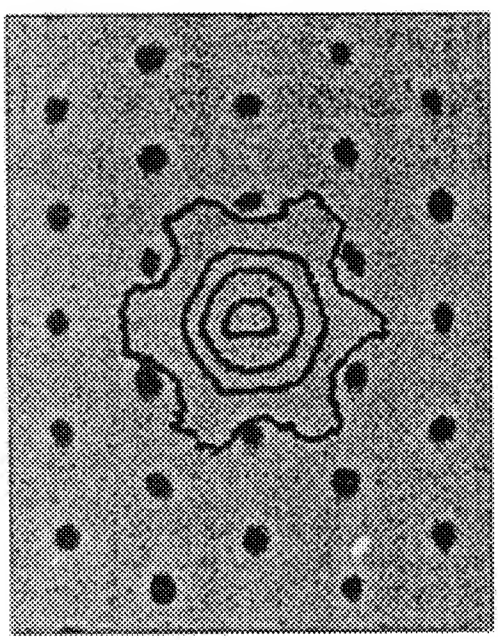
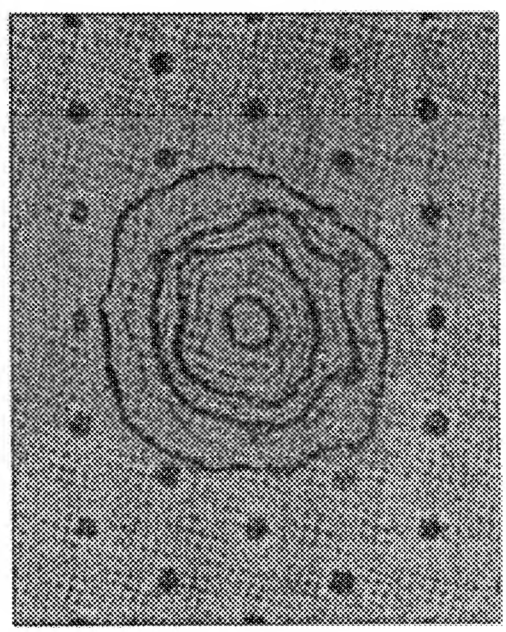


Fig.11(a).



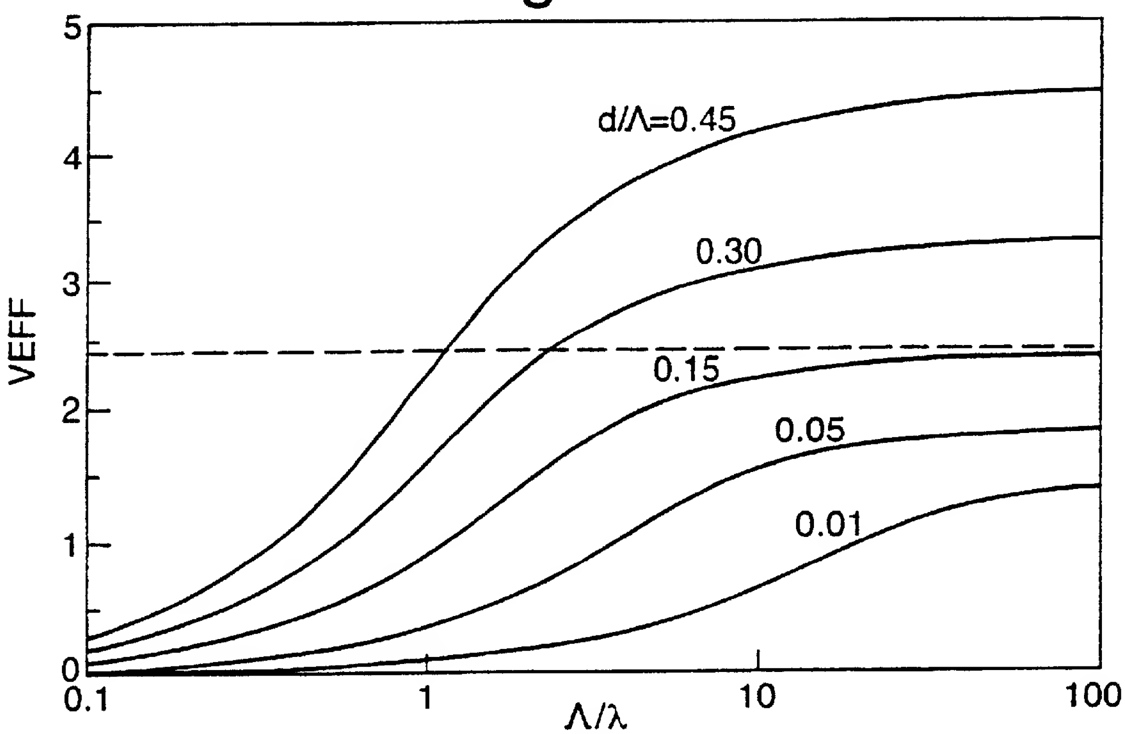
λ=633nm

Fig.11(b).



λ=1550nm

Fig.12.



SINGLE MODE OPTICAL FIBER

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to a single mode optical fiber which may be used for transmitting radiation at substantially higher powers than may be achieved using conventional means. The fiber does not suffer from non linear effects or optical damage at high powers to the same extent as conventional optical fibres. In particular, the fiber may be used as a single mode waveguide, in a single mode fiber laser or in a single mode fibre amplifier.

2. Description of the Related Art

Optical fibres are widely used to deliver light from one point to another and have application in communications, imaging and sensing. Conventionally, a typical optical fibre is a long strand of transparent material which is uniform along its length but which has a refractive index varying across its cross-section. For example, a central core region of higher refractive index is surrounded by a cladding region with a lower refractive index. Such a fibre may be made from fused silica with a cladding of pure silica surrounding a core made from silica into which deliberate impurities have been introduced to raise the refractive index. Light is confined in or near the core by the process of total internal reflection which takes place at the boundary between the core and the cladding.

In general, a fibre of this type may support more than one guided mode of propagation confined to the core (i.e. multi mode fibre), these modes travelling along the fibre at different phase velocities. However, if the core is made to be sufficiently small, only one guided mode of propagation will be confined to the core, the fundamental mode (i.e. a single mode fibre). That is, the distribution of light emerging from the fibre is unchanged when the conditions at the launch end of the fibre are changed and when the fibre itself is subjected to disturbances such as transverse compression or bending. Typically, a fibre designed to carry single mode light having a wavelength of 1500 nm may have a few percent of germanium dopant in the core, with a core diameter of 9 μm.

More recently, a photonic crystal fibre (PCF) has been developed comprising a cladding made of a transparent material in which an array of holes are embedded along the length of the fibre [J. C. Knight, et al., *Opt. Lett*. 21 (1996) p. 1547. *Errata: Opt. Lett*. 22 (1997) p. 484]. The holes are arranged transversely in a periodic array and are filled with a material which has a lower refractive index than the rest of the cladding, the core of the fibre comprising a transparent region which breaks the periodicity of the cladding. Typically, both the core and the cladding are made from pure fused silica and the holes are filled with air. The core diameter is approximately 5 μm and the flat-to-flat width of the whole fibre is around 40 μm, with a hole spacing of around 2–3 μm. If the diameter of the air holes in the fibre is a sufficiently small fraction of the pitch or spacing between the holes, the core of the fibre guides light in a single mode.

Single mode fibres have advantages over multi mode fibres in the field of long distance telecommunication, laser power delivery and many sensor applications due to the fact that a light signal carried by the fibre travels in only one mode and therefore avoids the problem of intermodal dispersion that is encountered with multi mode fibres. Also, at a given wavelength the intensity of light across a single mode fibre is guaranteed to follow a single smooth, known and unchanging distribution. This is regardless of how light

is launched into the fibre or of any disturbance of the fibre (e.g. time varying).

In many applications it is advantageous for an optical fibre to carry as much optical power as possible as for example, any fibre inevitably attenuates the light passing through it. For example, for a given detector sensitivity, the length of a communications link can be increased by increasing the radiation power input to the fibre. As another example, there are many high power laser systems in industrial applications which could be made more simply if light could be channelled via a fibre rather than using conventional optical systems. There are, however, limits to the amount of light that can be carried by known optical fibres at a given time.

In a conventional fibre, comprising a core region surrounded by a lower refractive index cladding region, the material from which the fibre is made will ultimately suffer irreversible damage if the light intensity within the fibre exceeds a threshold value. At lower intensities, a number of intensity dependent non-linear optical processes can occur which, although non destructive to the fibre, nevertheless can degrade or even destroy an optical signal.

These problems may be alleviated by increasing the size of the core of the fibre which, for a given power, reduces the intensity of the light in the fibre, therefore allowing a greater power to be carried before the threshold for non linear processes are reached. However, if the core diameter alone is increased the fibre will become multi mode. This may be compensated by reducing the index difference between the core and the cladding. Eventually however, it becomes difficult to control the uniformity of doping across the core. Furthermore, fibres with small index differences are susceptible to loss of light at bends. Therefore, there are limits to the extent to which an increased core size can be used to increase the power capacity of a single mode fibre.

Some of the non-linear effects are exacerbated by the presence of dopants in the core, which make the material more susceptible to these effects. At higher powers, doped fibres are more susceptible to irreversible damage. Dopants also make the fibre more susceptible to damage by ionising radiation which is an issue in the nuclear industry. This has been combated by making the core out of pure silica. Total internal reflection is maintained by introducing dopants to the cladding which reduce its refractive index and as less light is carried in the cladding than in the core, more power can be carried. However, this is limited by the fact that some of the light is carried in the doped cladding.

Furthermore, in conventional fibres, efficient coupling of high power lasers into the fibre is problematic as the light needs to be focused into a small spot and the intensity at the endface of the fibre is therefore larger than it would be if the core were larger. Optical damage at or near the endface of the fibre frequently limits the power of radiation that can be launched into it [S. W. Allison et al., *Appl. Opt*. 24 (1985) p. 3140]. The maximum continuous wave (cw) power that has been achieved in a conventional single-mode fibre is only around 15 W.

SUMMARY OF THE INVENTION

The invention overcomes the problem of the incompatibility of transmitting high power radiation using conventional fibres whilst retaining single mode behaviour. In particular, the fibre may be used as a waveguide for delivering radiation from one point to another, or may be used in a fibre amplifier or a fibre laser. The fibre may be capable of supporting a single mode of propagation of radiation having

a maximum power in the region of 100 W–2 kW. Furthermore, if the core is undoped, the fibre is less susceptible to irreversible damage at high intensities compared to conventional (doped) fibres. The effects of non-linear optical processes in the fibre are reduced and a high power signal output from the fibre does not therefore suffer degradation. The fibre has a further advantage in that high power radiation may be efficiently coupled into the fibre without the need for focusing to a small beam spot size.

According to one aspect of the present invention, an optical fibre for transmitting radiation comprises;

- a core comprising a substantially transparent core material, having a core refractive index, n, and a length, l, and having a core diameter of at least 5 μm and
- a cladding region surrounding the length of core material, wherein the cladding region comprises a first substantially transparent cladding material, having a first refractive index, and wherein the first substantially transparent cladding material has embedded along its length a substantially periodic array of holes, having a diameter, d, and being spaced apart by a pitch Λ, wherein the holes have a second refractive index which is less than the first refractive index,
- such that the dimensions of the hole diameter, d, and the pitch, Λ, co-operate to give single mode propagation within the optical fibre independent of input radiation wavelength for any value of the pitch, Λ, for a substantially fixed d/Λ ratio.

If the holes have a diameter, d, and are spaced apart by a pitch Λ, the optical fibre may be single mode independently of input radiation wavelength for any value of the pitch, Λ, for a substantially fixed d/Λ ratio. The invention provides the advantage that the fibre may be made single mode for any wavelength across an extended wavelength range compared to that which may be achieved using conventional fibre. This is because for any wavelength across the extended range, the fibre remains single mode for a fixed d/Λ ratio.

Preferably, the first substantially transparent cladding material may have a refractive index not less than the core refractive index. In a preferred embodiment, the core diameter may be at least 10 μm. In a further preferred embodiment, the diameter of the core may be at least 20 μm

In one embodiment of the invention, at least one hole in the array may be absent such that it forms the core of the optical fibre. The holes may be arranged in a substantially hexagonal pattern.

Preferably, the first substantially transparent cladding material may have a refractive index not than the core refractive index. In a preferred embodiment, the core diameter may be at least 10 μm. In a further preferred embodiment, the diameter of the core may be at least 20 μm.

In one embodiment of the invention, at least one hole in the array may be absent such that it forms the core of the optical fibre. The holes may be arranged in a substantially hexagonal pattern.

The holes may be a vacuum region or may be filled with a second cladding material. For example, the second cladding material may be any substantially transparent material, may be air or another gas (e.g. hydrogen or hydrocarbon) may be a liquid (e.g. water, any other aqueous solution or a solution of dyes) or may be a solid (e.g. a glass material having a different refractive index from that of the first cladding material).

The first substantially transparent cladding material may have a substantially uniform first refractive index and the core material may have a substantially uniform corn refractive index. The core material and the first substantially

transparent cladding material may be the same material. For example, at least one of the core material and the first substansially transparent cladding material may be silica. Preferably, the diameter of the holes is not less than the wavelength of light to be guided in the fibre. In a preferred embodiment of the invention the spacing between the holes, Λ, is not less than one quarter of the core diameter, c, and not more man one half of the core diameter, c.

In one embodiment of the invention, the substantially transparent core material may comprise a dopant material, for example rare earth ions, such as erbium.

According to a second aspect of the invention, a fibre amplifier for amplifying signal radiation comprises;

- a length of the optical fibre as described herein, for receiving signal radiation of selected wavelength and transmitting said signal radiation along its length, wherein the core material comprises a dopant material along at least part of its length,
- a source of radiation for emitting pump radiation of a different selected wavelength for input to the length of the optical fibre, such that said part of the doped core material amplifies the signal radiation under the action of the pump radiation and
- wavelength-selective transmission means for selectively transmitting the pump radiation into the length of the optical fibre and for selectively outputting the amplified signal radiation from the fibre amplifier.

For example, the wavelength-selective transmission means may comprise an input lens and an output lens for focusing radiation and a dichroic mirror for selectively reflecting pump radiation into the optical fibre and for and selectively transmitting the amplified input radiation to be output from the fibre amplifier. Alternatively, the wavelength-selective transmission means comprise a fibre directional coupler having a wavelength dependent response.

The dopant material may comprise rare earth ions, for example erbium ions.

According to another aspect of the invention, a fibre laser for outputting laser radiation comprises;

- a length of the optical fibre as herein described for selectively transmitting laser radiation having a selected wavelength along its length, wherein at least part of the length of the core material comprises a dopant material,
- a source of radiation for emitting pump radiation of a different selected wavelength for input to the length of the optical fibre, such that said doped core material amplifies the laser radiation under the action of the pump radiation,
- wavelength-selective transmission means for selectively transmitting the pump radiation into the length of the optical fibre and for selectively outputting the amplified laser radiation from the fibre laser and
- feedback means for selectively feeding back a part of the amplified laser radiation such that said amplified laser radiation passes along the length of the optical fibre repeatedly and is further amplified.

The dopant material may comprise rare earth ions, such as erbium ions.

In one embodiment of the fibre laser, the wavelength-selective transmission means and the feedback means together may comprise two dichroic mirrors, wherein each of the dichroic mirrors are situated at different positions along the length of the optical fibre and wherein the doped core material is situated between the positions of the two dichroic mirrors.

In an alternative embodiment of the fibre laser, the feedback means and the wavelength-selective transmission means together may comprise two fibre gratings formed at two different positions along the length of the optical fibre such that the doped core material is situated between the two fibre gratings.

In another embodiment of this aspect of the invention, the fibre laser may be a ring resonator fibre laser wherein the feedback means comprise:

means for directing light emerging from one end of the length of optical fibre having a doped core material into the other end of said length of optical fibre.

According to another aspect of the invention, a system for transmitting radiation in a single mode of propagation comprises;

a plurality of lengths of the optical fibre as herein described arranged in a series such that each length of optical fibre receives input radiation from the previous length of optical fibre in the series and transmits output radiation to the subsequent length of the optical fibre in the series and each length being separated by amplification means for amplifying the radiation output from a length of the optical fibre so as to maintain the power of the radiation transmitted by the lengths of optical fibre above a predetermined power.

In a preferred embodiment, the amplification means may comprise a fibre amplifier as herein described.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described by example only with reference to the following figures in which;

FIG. **1** shows schematic diagram of a conventional step index optical fibre,

FIGS. **2***a* and **2***b* show schematic diagrams of a photonic crystal fibre,

FIGS. **3***a* and **3***b* illustrates the advantage of coupling radiation into a relatively large photonic crystal fibre core,

FIG. **4** shows a large core photonic crystal fibre amplifier.

FIG. **5** shows a wavelength-selective coupler arrangement which may be used in the large core photonic crystal fibre amplifier shown in FIG. **6**,

FIGS. **6** and **7** show fibre laser configurations comprising a large core photonic crystal fibre,

FIGS. **8***a*, **8***b*, and **8***c* illustrates the stack and draw process which may be used to produce the large core photonic crystal fibre,

FIG. **9** shows an SEM image of the central region at the end face of a cleaved large core photonic crystal fibre of the invention,

FIG. **10** shows the near field pattern at the output of the photonic crystal fibre shown in FIG. **9**,

FIGS. **11***a* and **11***b* shows near field near field distribution plots at the endface of a photonic crystal fibre and

FIG. **12** shows effective V-value plots for a photonic crystal fibre.

BRIEF DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. **1**, a conventional step index fibre **1** comprises a circular core **2** of uniform refractive index n_1 and radius r surrounded by a cladding material **3** of unlimber refractive index n2. The number of guided modes the step index fibre **1** supports for light of wavelength λ is determined by the V-value, where V is given by;

$$V = \frac{2\pi r}{\lambda}\sqrt{n_1^2 - n_2^2} \qquad \text{Equation 1}$$

The step index fibre is single mode only if V is less than 2.405. Hence, conventional single mode step index fibres are typically operated so that V is a little less than 2.405.

Note: The threshold level V for multi mode propagation in large core photonic crystal fibres is different to the threshold value for conventional single mode step index fibres. In practice the threshold level for multi mode propagation in a large core photonic crystal fibre is somewhat higher an the value for a conventional single mode step index fibre.

In a conventional step index optical fibre, such as that shown in FIG. **1**, the material from which the fibre is made will ultimately suffer irreversible damage if the intensity of light propagating along the fibre exceeds a threshold value, For lower intensities of light, a number of non-linear optical processes can occur which can degrade or even destroy an optical signal. Although these problems can be alleviated by increasing the size of the core **2** of the fibre **1**, if the core radius alone is increased the fibre will become multi mode. The refractive index difference between the core **2** and the cladding **3** must therefore simultaneously be reduced to compensate.

The refractive indices of the core **2** and the cladding **3** may be controlled by introducing dopants into the material. Eventually, however, it becomes difficult to control the uniformity of doping across the core region **2**. Furthermore, fibres with small index differences are susceptible to loss of light at bends. This limits the extent to which the core size can be increased to increase the power of radiation the fibre is capable of transmitting, or the power capacity of the fibre. FIG. **2**(*a*) shows an optical fibre **4** of the invention which overcomes the power capacity problems associated with conventional fibres. The optical fibre **4** comprises a cladding of a first substantially transparent material **5**, in which an array of holes **6** are embedded along the length, l, of the fibre. The holes **6** are arranged transversely in a periodic array and may be filled with a second material having a lower refractive index than the first cladding material. This second material may be a solid, liquid or gas material or, alternatively, the holes may be empty (i.e. a vacuum). For example, the core material **7** and the first cladding material **5** may be made from pure fused silica and the holes **6** may be filled with air.

Substantially at the centre of the fibre cross section is a core region **7** of substantially transparent material which breaks the periodicity of the array of holes **6**. For example, the central hole in the array may be absent and the region of the first cladding material in and around the site of the absent hole forms the core **7** of the fibre **4**. The core of the fibre has a diameter, c, as shown in FIG. **2**(*b*). For the purpose of this description, the core diameter of the fibre, c, shall be taken to be substantially the distance between the centre of one hole adjacent to the core and the centre of a diametrically opposite hole adjacent to the core.

The array of holes may form a hexagonal-type pattern (for example, as shown in FIG. **2**(*a*)) but other hole patterns may also be envisaged.

In a conventional photonic crystal fibre, the outer width of fibre, w, is of the order of 40 μm, the centre-to-centre spacing (pitch, Λ) of the holes is approximately 2 μm. The solid core region has a diameter typically 4 μm, less than the diameter of the core of a conventional single mode fibre (see FIG. **1**),

for example as used in telecommunications applications. However, a photonic crystal fibre of this dimension is typically only be capable of transmitting radiation having a power of between 10–20 W. Such a fibre is not therefore suitable, for example, for use with high power laser systems which may have output powers of at least 1 kW.

According to one aspect of the invention, a single mode optical fibre for delivering radiation from one point to another comprises a photonic crystal fibre, as shown in FIG. **2**, wherein the diameter of the core **7** is at least 5 μm and preferably at least 10 μm. An increase in the core diameter of the photonic crystal fibre results in an increase in the amount of power that may be transmitted, it may be preferable for the diameter of the core to be larger still, for example in the region of 20–50 μm, depending on the particular application of the fibre. For the purpose of this specification, a photonic crystal fibre having a central core **7** with a diameter of at least 5 μm shall be referred to as a "large core photonic crystal fibre".

Furthermore, the large core photonic crystal fibre is capable of propagating radiation in a single mode. The fibre may therefore be used to transmit higher powers of radiation, due to the large core size, in a single mode of propagation than may be achieved conveniently using conventional optical fibres.

A large core photonic crystal fibre, having a core diameter of 50 μm, may be capable of supporting continuous wave radiation having a power of approximately 2 kW. This corresponds to the value obtained by extrapolating the best experimental results achieved for a conventional fibre. In a conventional, silica step index fibre, as shown in FIG. **1**, the maximum continuous wave intensity of radiation that can be transmitted before the onset of permanent damage is 100 MW cm^{-2} [W. Luthy, *Optical Engineering* 34 (1995) pp. 2361–2364]. For a core diameter of 12 μm this corresponds to a theoretical maximum power of only approximately 100 W. In practice, however, the theoretical maximum power is significantly reduced due to losses incurred in coupling radiation into the fibre and in fact the maximum continuous wave (cw) power that has been achieved in a conventional single-mode fibre is only around 15 W.

A further advantage of the large core photonic crystal fibre is that the coupling of radiation into the fibre may be achieved more easily. FIGS. **3**(*a*) and **3**(*b*) show schematic diagrams of, for example, laser radiation **8** being input to (a) a conventional photonic crystal fibre having a relatively small core and (b) a large core photonic crystal fibre, by means of a lens or lens arrangement **9**. Referring to FIG. **3**(*b*), if the core of the large core photonic crystal fibre **7** is comparable to the diameter of the beam of laser radiation, it may be possible to input the radiation **8** into fibre without the need for a lens **9**.

The single mode large core photonic crystal fibre has application in high power laser systems used in industry such as, for example, those used in laser machining applications where there is a need to direct high power laser radiation onto a material to be machined. It is inconvenient and impractical to move the laser to redirect the laser beam and so conventional optics are used to guide the laser radiation in the required direction. The large core photonic crystal fibre would enable high power laser radiation to be guided without the need for complex and bulky optics.

The large core photonic crystal fibre may also be used in communications applications. Conventionally, a length of conventional optical fibre (as shown in FIG. **1**) is used to deliver radiation from one point to another. As the intensity of radiation is attenuated as it is transmitted along the fibre, fibre amplifier devices, or repeaters, are used at various points along the length of the fibre to periodically enhance the power of transmitted radiation. Such devices detect a weak signal (i.e. the reduced power signal) emerging from a section of an optical fibre link, amplify it and send the amplified signal to the subsequent section of the link. The larger the power that can be supported by the fibre, the further the signal can travel through the optical fibre before amplification is required. Thus, the maximum power which can be carried by a fibre determines the spacing of the repeaters. However, the maximum power that can be carried by a fibre is limited by intensity-dependant non linear optical effects which can degrade the signal. A larger core area permits an increased power for a given intensity. The maximum fibre core area which may be used whilst still achieving a single mode of propagation therefore limits the repeater spacing to a minimum.

For given criteria of detectability, the repeater spacing for a standard fibre is 30 km [O. Audouin et al., *IEEE Photonics Technology Letters* (1995) pp. 1363–1365]. Using a large core photonic crystal fibre for transmitting radiation, having a fibre core diameter of approximately 50 μm, a repeater spacing of as much as 160 km may be sufficient (assuming the attenuation of the power in a photonic crystal fibre and a conventional fibre are similar). Thus, the transmission of optical signals can be achieved over large distances more conveniently and at less expense using the photonic crystal fibre. Furthermore, the large core photonic crystal fibre allows fibre links without the need for repeaters over distances where repeaters would otherwise be required when using conventional technology.

Referring to FIG. **4**, the large core photonic crystal fibre may also be used in a fibre amplifier system. A large core photonic crystal amplifier may typically comprise a length of fibre **4** having a core (not shown) which is doped with a small amount of a dopant material, such as erbium. The fibre amplifier also comprises a wavelength selective coupler (WSC) **12** and a pump radiation source **13** for emitting pump radiation **14**. The pump radiation **4** has a short wavelength compared to that of the input radiation **10** and is introduced into one end of the length of fibre **4** via the WSC **12**. Input signal radiation **10** from a radiation source **11**, or a previous length of optical fibre, is input to the length of the fibre **4** at the opposite end.

The purpose of the WSC **12** is to insert radiation of one wavelength (i.e. the pump wavelength) without diverting radiation of another wavelength (i.e. the input radiation wavelength). Hence, pump radiation **14** may be input along the same fibre **4** as the signal radiation **10**, without taking any signal radiation **10** out of the fibre **4**. The pump radiation **14** excites the dopant ions in the core of the fibre **4**, thus providing gain at the longer wavelength of the input radiation **10**. The input radiation **10** is therefore amplified. The wavelength-selective coupler **12** selectively transmits the long-wavelength input radiation, thus generating the amplified output signal **16**. This output signal **16** may be output through a length of fibre **15**.

Typically, a commercially available wavelength-selective coupler comprises lengths of input and output fibre, the input fibre(s) of which is a conventional doped fibre (as in FIG. **1**). In the large core photonic crystal fibre amplifier shown in FIG. **4**, it may be preferable to include only large core photonic crystal fibre in the system, to avoid losing intensity as the signal is input to and output from the WSC **12**.

The WSC **12** may be an all-fibre device such as a fused coupler or may be any fibre directional coupler device

having a wavelength dependant response. Alternatively, FIG. **5** shows an example of an optical arrangement **17** which may be used as the wavelength selective coupler. For example, the optical arrangement may comprise input and output lenses **18***a* and **18***b* respectively, and a dichroic mirror **19**. The mirror **19** is angled such that it reflects pump radiation **14** towards the input lens **18***a* and transmits input signal radiation **10**.

In a fibre amplifier representing the limit of conventional technology, comprising a step index optical fibre (as shown in FIG. **1**) with a core diameter of 20 μm and transmitting pulsed radiation having a 1 ns pulse length, a peak power of 100 kW has been achieved [P. Nouchi et al., *Proc. Conference on optical fibre communication* (1995) pp. 260–261]. Using the photonic crystal fibre amplifier shown in FIG. **4**, wherein the fibre **4** has a core diameter of approximately 50 μm, pulsed radiation having a 1 ns pulse and a peak power of at least 600 kW may be transmitted.

Another application of the large core photonic crystal fibre is in a fibre laser. Two possible configurations of a fibre laser are shown in FIGS. **6** and **7**, although there are many other configurations of fibre laser devices in which a large core photonic crystal fibre may be used. For example, the large core photonic crystal fibre may be used in a ring resonator fibre laser, wherein the ends of the fibre are joined together so that laser radiation is transmitted around the "ring" of fibre and is continuously amplified.

Referring to FIG. **6**, a fibre laser capable of outputting high power radiation may comprise a length of large core photonic crystal fibre **4** having a small amount of dopant material, such as erbium, within the core region (not illustrated). The fibre laser also comprises two dichroic mirrors, an input mirror **22** and an output mirror **23**, at either end of the fibre **4**. Radiation **24** from a source of pump radiation **25** (e.g. a laser) is input through the input mirror **22**. This creates gain in the doped fibre region **4** between the mirrors **22**,**23** by exciting the erbium ions in the core of the fibre. The spontaneous emission from the excited erbium ions generates a small amount of signal radiation within the fibre **4** (not shown within the fibre) having a longer wavelength than the pump radiation **24**. This signal radiation is amplified as it travels back and forth along the fibre, being reflected by the mirrors **22**,**23**.

Typically, the dichroic mirror **22** may be designed to reflect approximately 99% of the signal radiation whilst transmitting the pump radiation **24**, and the output dichroic mirror **23** may be designed to reflect approximately 80% of the laser radiation. Therefore, each time the signal radiation is reflected at the output mirror **23**, a fraction will also emerge as the output signal **25**.

A fibre laser is useful as it provides a source of laser radiation conveniently in the form of the fibre which may be easily coupled to subsequent lengths of optical fibre. Due to the high power capability of the large core photonic crystal fibre, a more powerful fibre laser output may be achieved than using conventional optical fibre.

Referring to FIG. **7**, an alternative configuration of a fibre laser may comprise fibre gratings **26** which have the function of the dichroic mirrors (FIG. **8**). This configuration has an advantage in that it is an all-fibre device. There are many configurations of a fibre laser in which the large core photonic crystal fibre may be included and the use of the fibre in such a device is not intended to be restricted to the two examples shown. As another example, the large core photonic crystal fibre may be used in a ring resonator fibre laser, whereby one end of the large core photonic crystal fibre is connected to the other such that laser radiation passes continuously round the "ring" of large core photonic crystal fibre and is continuously amplified.

Typically, the large core photonic crystal fibre **4** may be made using a repeated stack and draw process from rods of fused silica [J. C. Knight et al., *Opt. Lett.* 21 (1996) p. 1547. *Errata: Opt. Lett.* 22 (1997)p. 484], as illustrated in FIG. **8**. FIG. **8**(*a*) shows a cylindrical rod of fused silica **27** in which a hole **6** (FIG. **8**(*b*)) is drilled centrally along the length of the rod **8**. Six flats are milled on the outside of the rod at a regular distance from the hole, giving the rod **27** a hexagonal cross section about the central hole **6**. The rod **27** is then drawn into a cane **28** using a fibre drawing tower and the cane **28** is cut into the required length. The canes **28** are then stacked to form a hexagonal array of canes, as shown in FIG. **8**(*c*), which forms the fibre **4**. The cane at the centre of the array has no hole drilled through the centre and forms the core **7** of the fibre **4**. The complete stack of canes is then drawn down into the final fibre using the fibre drawing tower.

Alternative fabrication techniques may also be used, for example, if circular cylindrical silica capillaries are available these may be used as the basic fibre element (i.e. capillaries already having the form of the canes **28**). The would remove the need for the hole-drilling and milling steps in the aforementioned stack and draw process.

The fibre **4** comprises a first cladding material which is substantially transparent and is capable of being drawn into a fibre (as shown in FIG. **8**(*b*)). The core material may be any substantially transparent material but need not necessarily be the same material as the first cladding material. Preferably, the refractive index of the first cladding material is not less than that of the core material.

The holes **6** may be empty e.g. a vacuum or may be filled with any material, a second cladding material, which has a lower refractive index than that of the first cladding material and is also capable of being drawn into a fibre, or any such material which may be inserted into the holes when they have been drawn to their small size. For example, the holes may be filled with air or another gas (e.g. hydrogen or hydrocarbon), a solid material (e.g. a different glass material having a different refractive index from that of the first cladding material) or a liquid (e.g. water, aqueous solutions or solutions of dyes). A second cladding material within the holes need not necessarily be transparent. As is clear from this description, the phrase "holes" shall not be taken to be limited in meaning to regions of absence within the first cladding material.

If the diameter of the air holes in the fibre is a sufficiently small fraction of the pitch or spacing between the holes, the core of the fibre guides light in a single mode. Preferably, the diameter of the air holes is not less than the wavelength of light to be guided in the fibre. The spacing between the holes is preferably not less than one quarter of the core diameter and not more than one half of the core diameter. Most typically, the spacing between the holes may be approximately one half of the core diameter.

The first cladding material and the core may have a uniform refractive index or may have a varying refractive index. For example, as well as the central hole in the array being absent, or smaller or larger than the other holes may also be absent or may be filled with different materials. The core **7** may also be doped with a dopant material, for example erbium or other rare earth elements, as in the fibre laser device shown in FIGS. **6** and **7**.

FIG. **9** shows an SEM image of the central region at the end face of a cleaved PCF. The central hole is absent leaving

a core of diameter 22 μm bounded by the innermost six holes. The fibre is 180 μm across, and the relative hole size, d/Λ, is 0.12. FIG. **10** shows the near field pattern at the output of the large core PCF shown in FIG. **9** for incident light of wavelength 458 nm. The image is saturated at the centre of the pattern to show the weaker features at he edges. The periphery of the pattern is concave where it abuts the six innermost air holes.

Light of wavelength 458 nm was launched into the fibre and index matching fluid was applied to the structure to strip cladding modes. As the launch conditions were varied the output was observed. No multiple modes were excited in the near field pattern and the output of the PCF, as shown in FIG. **5**, was unaffected. Even though the core diameter is 50 times the wavelength of incident light, the fibre remained single mode. Scaling this result to a wavelength of 1550 nm, a similar PCF with a core diameter of 75 μm would also be single mode.

The behaviour of the large core photonic crystal fibre of the present invention may be understood in terms of the effective refractive index, n_2, of the cladding **5** at different wavelengths. FIGS. **11**(*a*) and **11**(*b*) show near field distribution plots at the endface **28** of a photonic crystal fibre **4** wherein the core material **7** and the first cladding material are silica and the holes **6** are filled with air.

Referring to FIG. **11**(*b*), at long wavelengths (e.g. 1500 nm), light propagating through the fibre **4** images the array of holes poorly (see FIG. **3**(*b*)) so a significant fraction of light propagates in the air holes **6**. The effective refractive index of the cladding material **5**, e.g. silica and air, is therefore reduced relative to the refractive index of pure silica, n_1 (i.e. the refractive index of the core **7**). Referring to FIG. **11**(*a*), at short wavelengths (e.g. 600 nm) light propagating along the fibre **4** images the array of holes **6** clearly and is substantiay excluded from propagating through them. The effective refractive index, n_2, of silica cladding **5** surrounding the core **7** is therefore closer to the refractive index of pure silica (i.e. the refractive index of the core **7**), n_1.

Hence, referring back to Equation 1, as the wavelength of light propagating through the fibre **4** is decreased, the V-value is raised by the explicit dependence on the wavelength λ. This increase is at least partially compensated by the reduction of the factor $(n_1^2-n_2^2)^{1/2}$, where n_2 and n_1 are the effective refractive index of the silica cladding and the refractive index of pure silica (and the core **7**) respectively. This makes the V-value less dependent on wavelength and therefore makes an extended wavelength range possible for which V is below the threshold for multi mode guidance for the structure.

The wavelength dependence of V is not only reduced but is in fact completely eliminated in the limit of short wavelength. This is shown in FIG. **12** which shows a graph of the effective V-value (V_{eff}) of a fibre as the ratio of the hole pitch Λ to the wavelength λ varies. Each curve corresponds to a given ratio of the diameter d of the holes **6** to the pitch Λ. The V_{eff}–d/Λ curves are calculated by first calculating the effective refractive index n_1 of the cladding material **5** and then calculating V_{eff} from Equation 1. The calculation assumes the radius of the core **7** is equal to the pitch Λ.

FIG. **12** shows that for each ratio of d/Λ, V is bounded above by the value as the ratio Λ/λ tends to infinity. This behaviour is in contrast to that of the conventional step index fibre for which V tends to infinity as r/λ tends to infinity. Unlike a conventional step index fibre, a large core photonic crystal fibre may therefore be constructed so as to be single mode for any scale of structure. The fibre may therefore be single mode for any value of the pitch Λ provided that the ratio of d/Λ, where d is the diameter of the holes **6**, is fixed.

The properties of the large core photonic crystal fibre make its suitable for use in several applications including use as a high power communications link, a high power fibre amplifier and a high power fibre laser. The fibre may also be used for the delivery of large optical powers for industrial applications, for example laser machining, and medical applications.

What is claimed is:

1. An optical fibre for transmitting radiation comprising;

a core comprising a substantially transparent core material, having a core refractive index, n, and a length, l, and having a core diameter, of at least 5 μm and

a cladding region surrounding the length of core material, wherein the cladding region comprises a first substantially transparent cladding material, having a first refractive index, and wherein the first substantially transparent cladding material has embedded along its length a substantially periodic array of holes, having a diameter, d, and being spaced apart by a pitch Λ, wherein the holes have a second refractive index which is less than the first refractive index,

such that the dimensions of the hole diameter, d, and the pitch, Λ, co-operate to give single mode propagation within the optical fibre independent of input radiation wavelength for any value of the pitch, Λ, for a substantially fixed d/Λ ratio.

2. The optical fibre of claim **1**, wherein the first substantially transparent cladding material has a refractive index not less than the core refractive index.

3. The optical fibre of claim **1**, wherein the core diameter is at least 10 μm.

4. The optical fibre of claim **3**, wherein the core diameter is at least 20 μm.

5. The optical fibre of claim **1**, wherein at least one hole in the array is absent such that it forms the core of the optical fibre.

6. The optical fibre of claim **1**, wherein the first substantially transparent cladding material has a substantially uniform first refractive index.

7. The optical fibre of claim **1** wherein the core material has a substantially uniform core refractive index.

8. The optical fibre of claim **1** wherein the core material and the first substantially transparent cladding material are the same.

9. The optical fibre of claim **1** wherein at least one of the core material and the first substantially transparent cladding material are silica.

10. The optical fibre of claim **1** wherein the diameter of the holes, d, is not less than the wavelength of light to be guided in the fibre.

11. The optical fibre of claim **1** wherein the spacing between the holes, Λ, is not less than one quarter of the core diameter, c, and not more than one half of the core diameter, c.

12. The optical fibre of claim **1**, wherein the holes are a vacuum.

13. The optical fibre of claim **1** wherein the holes are filled with a second cladding material.

14. The optical fibre of claim **13** wherein the second cladding material is air.

15. The optical fibre of claim **13** wherein the second cladding material is a liquid.

16. The optical fibre of claim **13** wherein the second cladding material is a substantially transparent material.

17. The optical fibre of claim **1** wherein the substantially transparent core material comprises a dopant material.

18. The optical fibre of claim **1** wherein the holes are arranged in a substantially hexagonal pattern.

19. A fibre amplifier for amplifying signal radiation comprising;

a length of the optical fibre in claim **1**, for receiving signal radiation of selected wavelength and transmiting said input radiation along its length, wherein the core material comprises a dopant material along at least part of its length,

a source of radiation for emitting pump radiation of a different selected wavelength for input to the length of the optical fibre, such that said part of the doped core material amplifies the signal radiation under the action of the pump radiation and

wavelength-selective transmission means for selectively transmitting the pump radiation into the length of the optical fibre and for selectively outputting the amplified signal radiation from the fibre amplifier.

20. The fibre amplifier of claim **19**, wherein the wavelength-selective transmission means comprise;

an input lens and an output lens for focusing radiation and radiation and

a dichroic mirror for selectively reflecting pump radiation into the optical fibre and for and selectively transmitting the amplified signal radiation to be output from the fibre amplifier.

21. The fibre amplifier of claim **19** wherein the wavelength-selective transmission means comprise a fibre directional coupler having a wavelength dependent response.

22. The fibre amplifier of claim **19** wherein the dopant material comprises rare earth ions.

23. The fibre amplifier of claim **22** wherein the rare earth ions are erbium ions.

24. A fibre laser for outputting laser radiation comprising;

a length of the optical fibre in claim **1** for selectively transmitting laser radiation having a selected wavelength along its length, wherein at least part of the length of the core material comprises a dopant material,

a source of radiation for emitting pump radiation of a different selected wavelength for input to the length of the optical fibre, such that said doped core material amplifies he laser radiation under the action of the pump radiation,

wavelength-selective transmission means for selectively transmitting the pump radiation into the length of the optical fibre and for selectively outputting the amplified laser radiation from the fibre laser and

feedback means for selectively feeding back a part of the amplified laser radiation such that said amplified laser radiation passes along the length of the optical fibre repeatedly and is further amplified.

25. The fibre laser of claim **24** wherein the dopant material comprises rare earth ions.

26. The fibre laser of claim **25** wherein the rare earth ions are erbium.

27. The fibre laser of claim **24** wherein the wavelength-selective transmission means and the feedback means together comprise two dichroic mirrors, wherein each of the dichroic mirrors are situated at different positions along the length of the optical fibre and wherein the doped core material is situated between the positions of the two dichroic mirrors.

28. The fibre laser of claim **24** wherein the feedback means and the wavelength-selective transmission means together comprise two fibre gratings formed at two positions along the length of the optical fibre such that the doped core material is situated between the two fibre gratings.

29. The fibre laser of claim **24** wherein the feedback means comprise:

means for directing light emerging from one end of the length of optical fibre having a doped core material into the other end of said length of optical fibre.

30. A system for transmitting radiation in a single mode of propagation comprising:

a plurality of lengths of the optical fibre in claim **1** arranged in a series such that each length of optical fibre receives input radiation from the previous length of optical fibre in the series and transmits output radiation to the subsequent length of the optical fibre in the series and each length being separated by amplification means for amplifying the radiation output from a length of the optical fibre so as to maintain the power of the radiation transfixed by the lengths of optical fibre above a predetermined power.

31. The system of claim **30**, wherein said amplification means comprise a fibre amplifier.

* * * * *

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(12) **United States Patent**
Liou et al.

(10) **Patent No.: US 7,031,612 B2**
(45) **Date of Patent: Apr. 18, 2006**

(54) **OPTICAL TRANSPONDERS AND TRANSCEIVERS**

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(73) Assignee: **Multiplex, Inc.**, South Plainfield, NJ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 804 days.

(21) Appl. No.: **09/907,283**

(22) Filed: **Jul. 17, 2001**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
H04B 10/00 (2006.01)

(52) **U.S. Cl.** **398/135**; 398/136; 398/137; 398/138; 398/139; 398/140; 398/182; 398/202; 398/211; 372/40; 372/43; 372/46; 372/55

(58) **Field of Classification Search** 398/135–139, 398/140, 173, 182, 198, 202, 211; 372/40, 372/55, 46, 43
See application file for complete search history.

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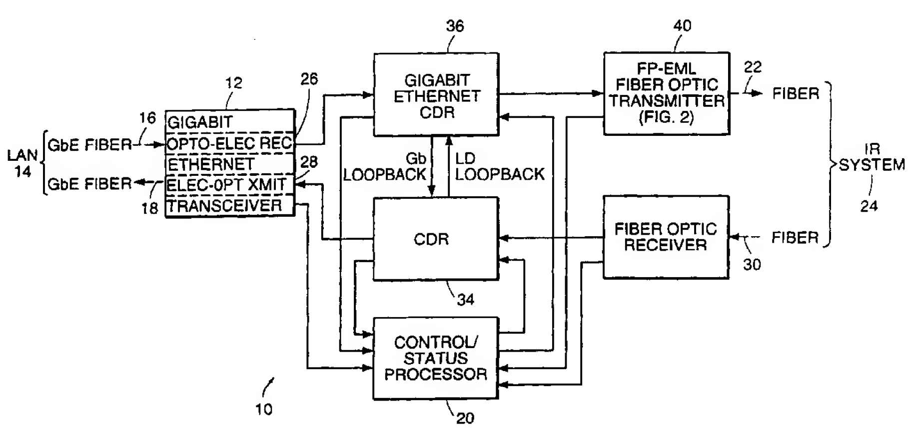
Assistant Examiner—Chau M. Nguyen
(74) *Attorney, Agent, or Firm*—Testa, Hurwitz & Thibeault, LLP

(57) **ABSTRACT**

An optical transponder/transceiver for intermediate range (e.g., 10–50 km) optical communication applications utilizes an electroabsorption modulated laser for the transmitting device. Preferably, the laser operations at a wavelength of approximately 1310 nm and comprises an electroabsorption modulated Fabry-Perot laser.

11 Claims, 4 Drawing Sheets



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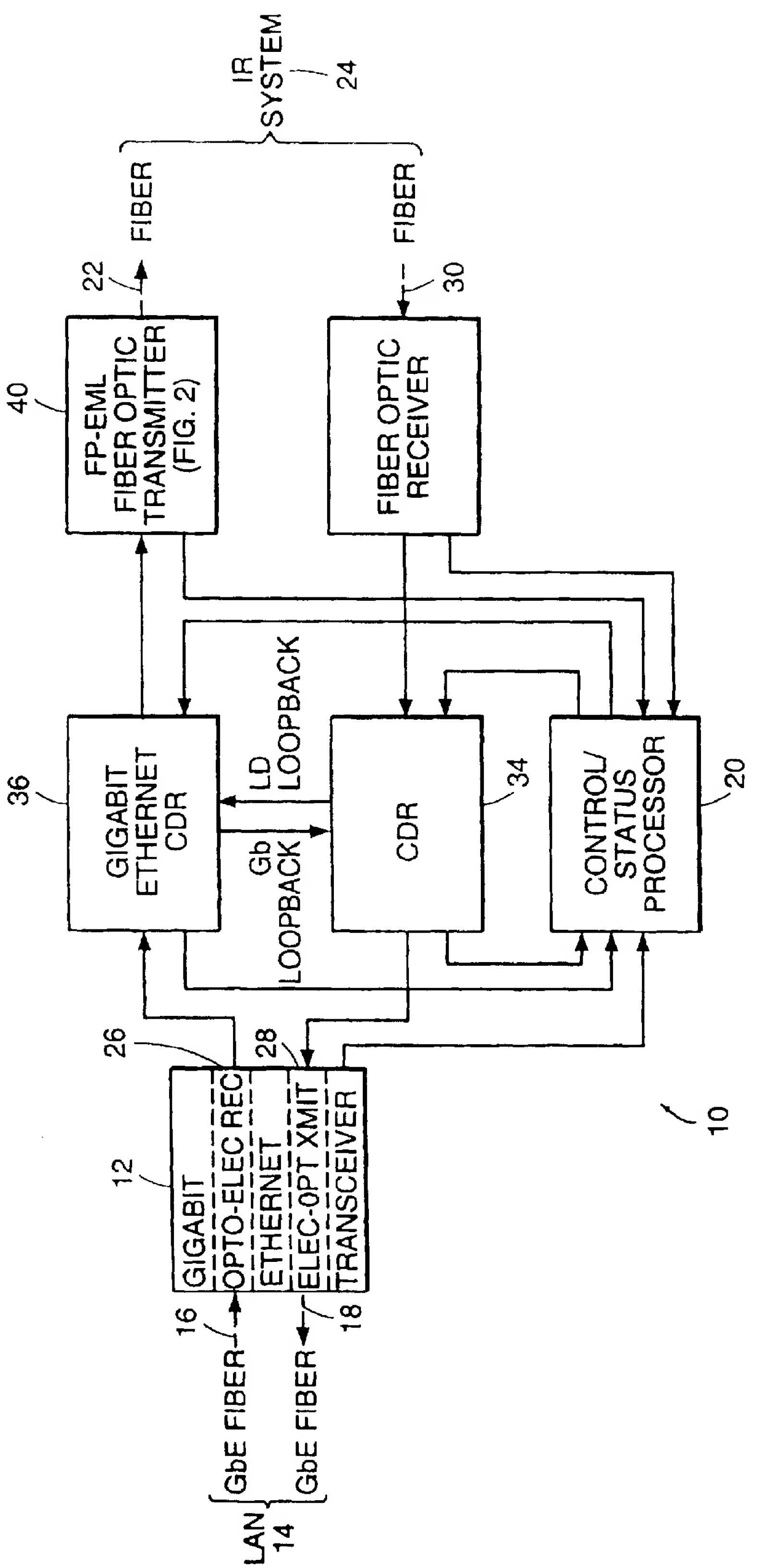
IR SYSTEM
24
FIBER
FIBER
22
30
40
FP-EML FIBER OPTIC TRANSMITTER (FIG. 2)
FIBER OPTIC RECEIVER
36
GIGABIT ETHERNET CDR
LD LOOPBACK
Gb LOOPBACK
CDR
34
CONTROL/ STATUS PROCESSOR
20
26
28
12
GIGABIT OPTO-ELEC REC ETHERNET ELEC-OPT XMIT TRANSCEIVER
16
18
GbE FIBER
GbE FIBER
LAN
14
10

FIG. 1

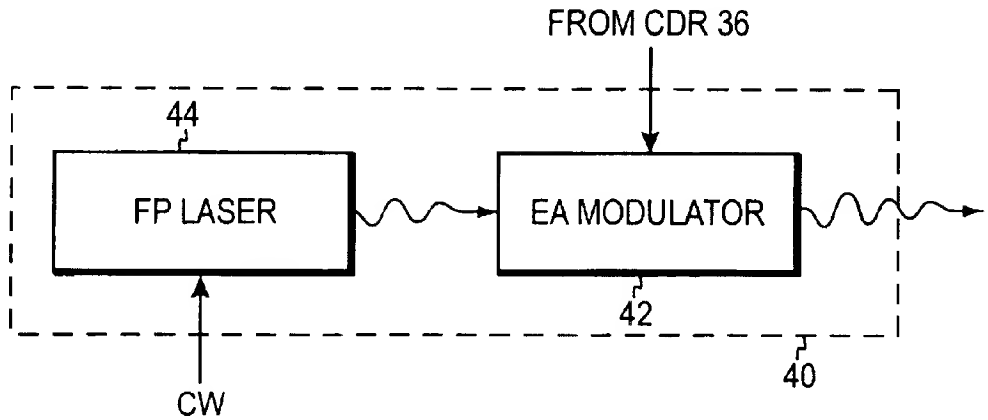
FROM CDR 36
44
FP LASER
EA MODULATOR
42
40
CW

FIG. 2

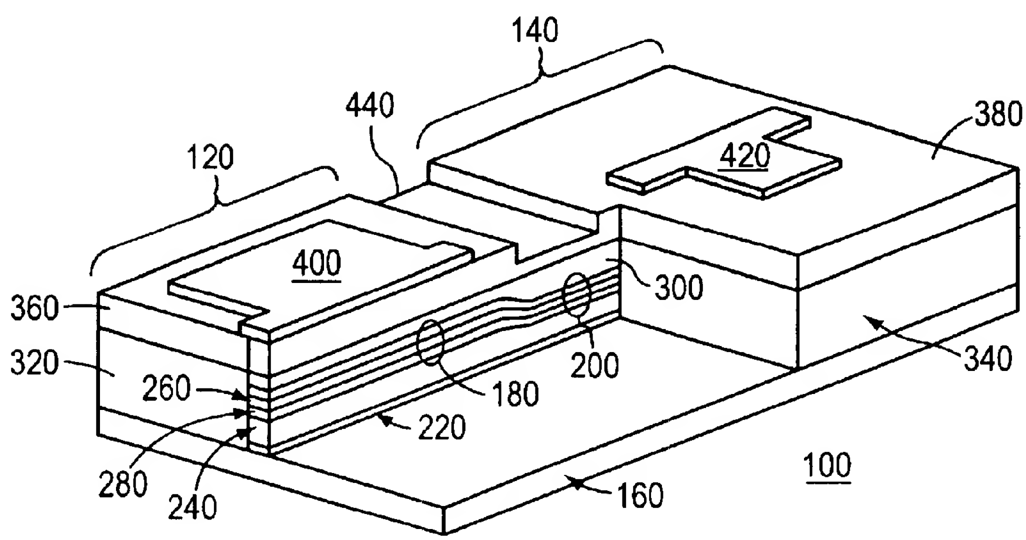
140
440
380
120
420
400
360
300
320
260
180
200
340
220
100
280
240
160

FIG. 3

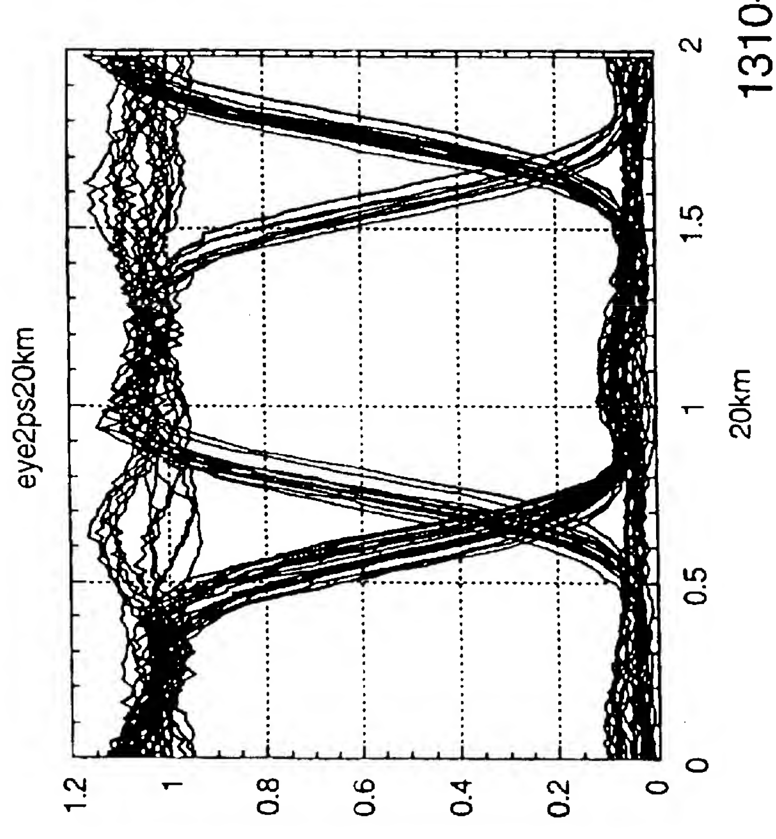

FIG. 4A-1

1310-EML

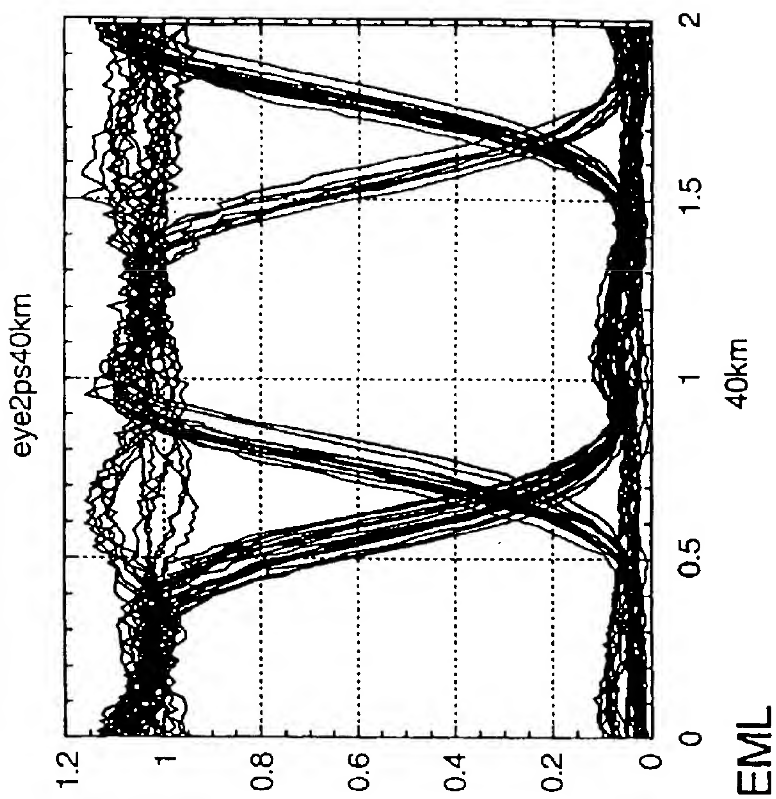

FIG. 4A-2

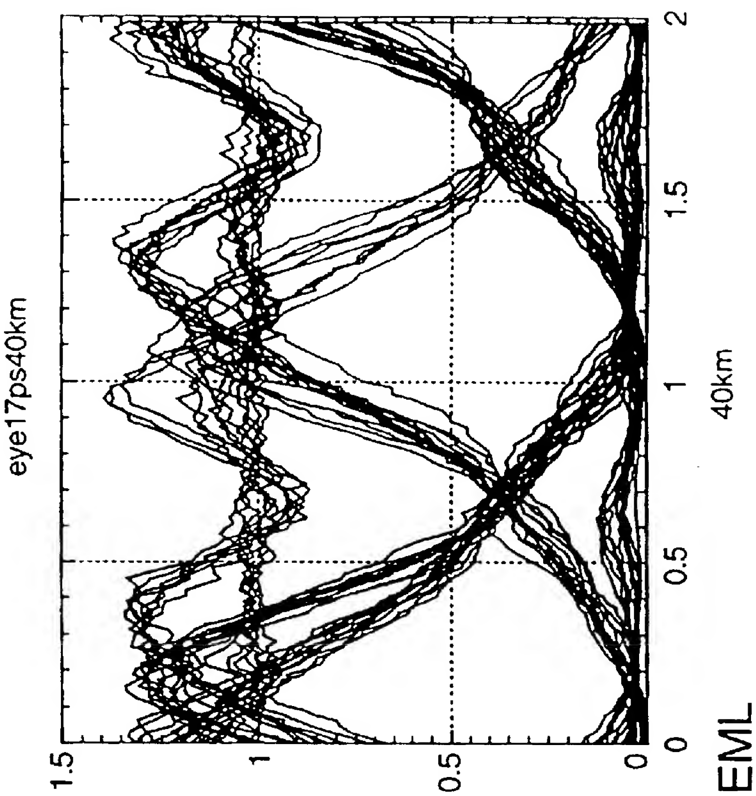

FIG. 4B-2

1550-EML

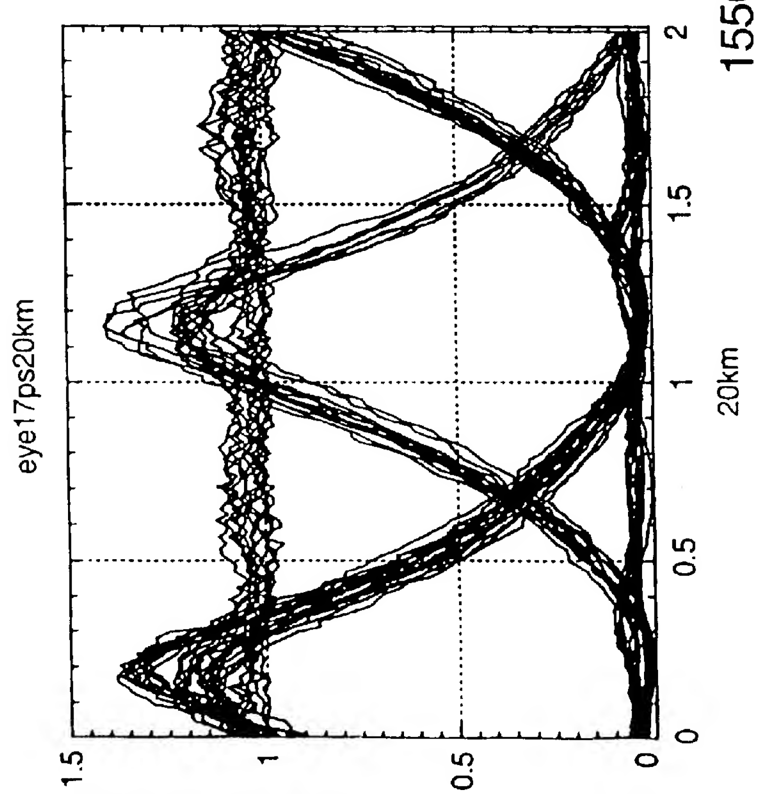

FIG. 4B-1

OPTICAL TRANSPONDERS AND TRANSCEIVERS

CROSS REFERENCE TO RELATED APPLICATION

This application claims the prior art Provisional Application No. 60/218,919, filed Jul. 18, 2000.

TECHNICAL FIELD

The present invention relates to optical transponders and transmitters and, more particularly, to such transponders and transceivers using a 1310 nm electroabsorption modulated Fabry-Perot laser module as the optical transmitting device.

BACKGROUND OF THE INVENTION

Fiber optic (digital) communication systems are now preferred over and being installed to replace a variety of conventional cable network systems, primarily due to their wide spectral characteristics that allow a user to transmit broadband signals, as well as their flexibility in terms of the available choices for data rates. However, at very high data rates (for example, Gb/s or higher), the limited performance capabilities of readily available and reduced-cost electronic circuits and components has limited the end-to-end link distance of fiber optic networks to essentially that of a local area network, covering a distance of on the order of 5 km or less. As telecommunications customers are increasingly relying upon the rapid information access and transport capabilities of digital communication networks, it has become apparent to most service providers that the need exists to extend the range of high speed data communications to distances well beyond that of the local area network limit, but in a manner that is both transparent and cost acceptable to the end user.

In some of the network solutions, an optical transponder is used to extend the range of a full duplex fiber optical communication system upwards of 30 to 100 km. The fiber optic transponder includes a front-end (short haul) transceiver unit that contains an opto-electronic converter-receiver and an associated electro-optic converter transmitter. The front end's opto-electronic converter-receiver is coupled to an optical fiber of a local area network, through which gigabit digital data is supplied that is to be transported over a long distance fiber optic link for delivery to a recipient customer site. While the LAN fiber may be either multimode or single mode, the long distance fiber is required to be single mode, exhibiting a zero dispersion wavelength of either 1310 nm or 1550 nm, where the 1550 nm single mode fiber is primarily used in the prior art for the longest distance transmission systems. The electro-optic converter-transmitter unit is operative to convert electrical signals that have been regenerated from long distance optical data received from a far end site into optical signals for delivery to the LAN.

The optical transmitter included in the output of the transponder preferably includes a high speed, low jitter, current-limiting driver, which minimizes jitter generation, and thereby optimizes range extension margin. In most prior art transmitter arrangements, the current driver is controlled by a regulated drive current controller to ensure that the output extinction ratio of the laser diode is able of precise setting and remains highly stable, thereby minimizing wavelength chirp, so as to prevent undesirable dispersion effects through a dispersive, long fiber. To minimize potential dispersion for the long distance fiber link, the laser diode of choice in the prior art has been the distributed feedback (DFB), due to its narrow spectral width and an output wavelength that matches the zero dispersion wavelength of long haul transmission fiber (i.e., 1550 nm).

In some newer arrangements, 1550 nm electroabsorption modulated lasers (EMLs) are being deployed in high speed, 2.5 Gb/s and 10 Gb/s fiber optic networks. The advantage of these devices, as compared to the DFB lasers mentioned above, is that electroabsorption modulated lasers exhibit highly superior eye diagrams, with less pulse distortion/ringing, minimal chirp characteristics, high extinction ratio, and simplified driver circuitry. At the same time, there is a rapid increase in the deployment of fiber optic-based equipment which utilize transponder, transceiver and transmitter modules operating at 10 Gb/sec and at wavelengths near the 1310 nm dispersion minimum of optical fiber. Currently, directly modulated 1310 nm DFB or Fabry-Perot (FP) lasers are utilized in these applications. However, directly modulated DFB and FP lasers exhibit severe limitations due to relaxation oscillation effects and the difficulties of modulating the drive current at 10 Gb/sec. Thus, a need remains in the art for a laser source that is useful in the "intermediate" range (e.g., 10–50 km) between short haul (5 km) and long haul (over 100 km) applications, when using optic fiber with a zero dispersion wavelength at 1310 nm, that overcomes the drawbacks of the directly modulated DFB and FP lasers.

SUMMARY OF THE INVENTION

The need remaining in art is addressed by the present invention, which relates to optical transponders and transmitters and, more particularly, to such transponders and transceivers using a 1310 nm electroabsorption modulated Fabry-Perot (FP) laser module as the optical transmitting device.

In accordance with the present invention, an electroabsorption modulated laser is used in a transceiver or transponder arrangement and is formed to include a Fabry-Perot laser section operated in CW mode and an electroabsorption modulator that is responsive to the incoming (electrical) digital data signal to generate the modulation input for the FP laser section. The FP EML device is formed as a monolithic structure which, as a result of simplified fabrication processes, is relatively inexpensive to manufacture and exhibits a relatively high yield.

It is an advantage of the present invention that the use of a FP EML-based transceiver or transponder operating at 1310 nm is advantageous in short and intermediate reach applications where the superior eye diagram characteristics and voltage modulation can be utilized to offset cost in the rest of the system.

Other and further advantages of the present invention will become apparent during the course of the following discussion and by reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings,

FIG. **1** contains a simplified diagram of an exemplary optical transponder, illustrating the position and operation of the laser diode module;

FIG. **2** is a block diagram of an exemplary FP-EML laser transmitter suitable for use in the transponder of FIG. **1**;

FIG. **3** is an isometric view of an exemplary FP-EML device; and

FIGS. **4**(*a*) and **4**(*b*) contain graphs comparing the performance of a 1310-EML transmitter, formed in accordance with the present invention, versus a 1550-EML, for intermediate distances of 20 km and 40 km.

DETAILED DESCRIPTION

FIG. **1** illustrates the architecture of an exemplary transponder **10** for interfacing a short haul high speed fiber optic data link, such as a Gigabit Ethernet (GbE) LAN, with an intermediate range fiber optic link. As mentioned above, a number of optical communication applications have emerged which utilize "intermediate" distance range of 10–50 km (as opposed to the LAN application range of 5 km and the "long haul" applications using upwards of 100 km). Referring to FIG. **1**, transponder **10** includes a front-end that includes a transceiver **12** for communicating with LAN **14** via, for example, a pair of GbE optical fibers **16**, **18** (using a conventional optical coupling arrangement, not shown). A control and status monitoring processing **20** may be included in transponder **10** to aid the operator in assessing the performance of transponder **10**.

As an example using the particular arrangement illustrated in FIG. **1**, customer-sourced gigabit digital data (having, for example, a data rate of 1.25 GB/s) is to exit LAN **14** and be transported through transponder **10** to an outgoing fiber **22** associated with an intermediate range communication system **24** (and presumably, applied as an input to another LAN at the far end of the intermediate range system). In this outgoing direction (i.e., from LAN **14**), the front end of transceiver **12** contains an opto-electronic converter-receiver **26**, the input of which is coupled to a first, incoming section of optical fiber **16** of LAN **14**. Opto-electronic converter-receiver **26** is operative to convert incoming optical data signals supplied over incoming fiber **16** into electrical signals that are representative of the Ethernet-formatted customer data. Transceiver **12** also includes a (short haul) electro-optic converter-transmitter unit **28**, the output of which is coupled to the second (out-going) optical fiber **18** of LAN **14**. The electro-optic converter-transmitter unit **28** is operative to convert electrical signals that have been regenerated from light signals modulated with (Gigabit Ethernet formatted) data that has been transported over an incoming fiber **30** of the intermediate range fiber optic link **24** and destined for LAN **14**.

Due to the distance (for example, 10–50 km) the optical signals must propagate between transponder locations, coupled with the timing jitter of low-cost short-haul transceiver components, the modulated light signal transported by intermediate range fiber optic link **24** can be expected to undergo significant (and unacceptable) degradation (in terms of amplitude, signal shape and timing) by the time it reaches the far end of link **24**. Accordingly, the use of a clock/data regenerator **34** (CDR) in both the transmit and receive paths, in combination with precision-controlled optical signal processing components within processor **20**, serves to pre- and post-compensate for distortion and timing jitter, and thereby ensure accurate regeneration of the data at each end of the intermediate range link. The highly precise and jitterless serial data stream signal produced by transmitter regenerator **36** is coupled as a data drive input to FP-EML laser transmitter **40**, where transmitter **40** is illustrated in more detail in FIG. **2**.

In particular, FP-EML laser transmitter **40** comprises an input electroabsorption (EA) modulator section **42**, which receives as an electrical input the data signal described above. Formed on the same substrate as EA modulator **42** is a Fabry-Perot (FP) laser section **44**, comprising an MQW active region configured to lase at 1310 nm. A CW input signal is applied to FP laser section **44** such that the optical output will be modulated with the data signal passing through EA modulator **42**. As shown in FIG. **1**, the output from transmitter **40** is then coupled into fiber **22** for transmission along intermediate range data link **24** to a far-end LAN (not shown). In the reverse direction, input optical signals received over optical fiber **30** from intermediate range data link **24** is applied as an input to an optical receiver **38**, which functions to convert the received optical signal into an electrical equivalent. The converted electrical signal is then passed through CDR **34** for re-shaping and regeneration and then applied as an input to electro-optic transmitter **28** within transceiver **12**. The regenerated electrical signal is then converted to an optical output signal and passed along optical fiber **18** into LAN **14**.

A cut-away isometric view of a Fabry-Perot electroabsorption modulated laser (FP-EML) **100** useful in the transponder arrangement of FIG. **1** is illustrated in FIG. **3**. As mentioned above, FP laser **120** section is operated in CW mode and EA modulator section **140** is subjected to the input data signal from LAN **14**. Both FP laser **120** and EA modulator **140** are formed on a common InP substrate **160**, where FP laser **120** comprises a multiple quantum well (MQW) action region **180** which transitions to become a MQW action region **200** in EA modulator **140**. A selective area growth (SAG) technique may be used to form this MQW structure and insure that active region **180** in laser **120** is emissive (relatively thick MQW layers), while active region **200** in EA modulator **140** is absorptive (relatively thin MQW layers). The transition between the MQW layer thickness is evident in area **220** of the cut-away view of FIG. **3**.

Referring to FIG. **3**, FP-EML **100** comprises a first n-InP buffer layer **220**, covered by a separate confinement heterostructure (SCH) InGaAsP layer **240**. Preferably, first n-InP buffer layer **220** comprises a thickness on the order of 100 nm and SCH layer **240** comprises a thickness of approximately 70 nm and exhibits a band gap wavelength of 1.15 micron. MQW action regions **180** and **200** are formed over SCH layer **240**, preferably using the SAG process. In a preferred embodiment, between 7 and 9 pairs of "barrier" **260** and "well" **280** layers are formed, where for FP laser section **120**, the layers are grown in a manner to provide lasing at the desired wavelength. For some embodiments, a device which lases in the wavelength range of 1260–1600 nm is desirable. Other arrangements require a device which lases in the wavelength range of 700–1000 nm. Some conventional EML devices have exhibited excellent characteristics at a wavelength of approximately 1550 nm. An advantage of the FP-EML structure of the present invention is that the FP device can be formed to exhibit a wavelength of 1310 nm, which cannot be achieved using a conventional DFB device in the EML structure. In general, the use of a SAG process to form the MQW active region allows for the FP-EML device of the present invention to be tailored to emit at a wavelength chosen by the designer for a specific system implementation.

Referring back to FIG. **3**, a second InGaAsP SCH layer **300** is formed over MWQ active regions **180**, **200**. Current blocking in the device is provided by Fe-doped InP barriers **320** and **340**, formed on either side of the active waveguiding region of FP-EML **100**. A p-InP cladding layer **360** is then formed on the top surface of device **100**, followed by a p-InGaAs contact layer **380**. A first electrical contact pad **400**, associated with FP laser **120**, is deposited on contact layer **380** over the location of active region **180**. A second electrical contact pad **420**, associated with EA modulator **140**, is deposited on contact layer **380** over the location of active region **200**. In a preferred embodiment, first and second electrical contact pads comprise a tri-layer Ti—Pt—Au structure.

In accordance with the properties of the FP-EML device of the present invention, an isolation trench **440** is formed between FP laser section **120** and EA modulator **104**, as shown in FIG. **3**. In a preferred embodiment, trench **440** comprises a depth of approximately 0.7 microns (into p-InP cladding layer **360**) and a width of approximately 20 microns. Trench **440** may be formed using conventional reactive ion etching (RIE) techniques and is used to reduce electrical crosstalk between FP laser section **120** and EA modulator section **140**.

FIGS. **4**(*a*) and **4**(*b*) contain graphs of the "eye diagrams" for both a transmitter using a 1310-EML of the present invention (FIG. **4**(*a*)), and a conventional transmitter using a 1550-EML. In particular, the eye diagrams illustrate the effects of dispersion on the transmission at a rate of 10 Gb/s over a distance of 20 km and 40 km. The improvement in the shape of the eye diagram (interpreted as a reduction in dispersion), and the resultant improvement in bit error rate is evident. Very little "overshoot" in the eye is found at 20 km or 40 km when using the 1310-EML transmitter of the present invention. The dispersion for the 13010-EML transmitter is calculated to be approximately 2 ps/km/nm, while the dispersion for the 1550-EML is 17 ps/km/nm.

The above-described embodiments of the present invention are to be considered as exemplary only, with the scope of the present invention limited only by the claims appended hereto.

What is claimed is:

1. An optical transponder module for providing transport of optical communications between a first network and a second network over an intermediate range optical communication system, the module comprising

a front-end transceiver for receiving input optical communication from the first network and converting said input into an electrical data output, and receiving input electrical data from the second network and converting said electric input into an output optical signal and transmitting said output optical communication to said first network;

an intermediate range optical transmitter, responsive to the electrical data output from the front-end transceiver for converting said electrical data into an optical output signal for transmission over said intermediate range optical communication system to said second network; and

an intermediate range optical receiver, responsive to optical data input from the second network for converting said optical input into an electrical data signal applied as an input to said front-end transceiver for conversion to an optical output signal transmitted to said first network,

wherein said intermediate range optical transmitter comprises an electroabsorption modulated laser including an electroabsorption modulator section responsive to the electrical data output from said front-end transceiver and a Fabry-Perot laser section responsive to the electroabsorption modulator for providing a modulated optical output signal, the electroabsorption modulator section comprising a first multiple quantum well active region comprising a plurality of barrier layers and a plurality of well layers, the Fabry-Perot laser device section comprising a second multiple quantum well active region comprising a plurality of barrier layers and a plurality of well layers, wherein each of said barrier layers and said well layers of said second multiple quantum well active region are thicker than each of said barrier layers and said well layers of said first multiple quantum well active region, respectively.

2. An optical transponder as defined in claim **1** wherein the intermediate range optical transmitter comprises an isolation trench for reducing electrical cross-talk between the Fabry-Perot laser section and the electroabsorption modulator.

3. An optical transponder as defined in claim **1** wherein the Fabry-Perot laser section and the electroabsorption modulator section form a monolithic structure.

4. An optical transponder as defined in claim **1** wherein the Fabry-Perot laser section operates at a wavelength of approximately 1310 nm.

5. An optical transponder as defined in claim **1** wherein the signals propagate over a communications network having an intermediate range of approximately 10–50 km.

6. An optical transceiver for operation in an intermediate range optical communication system, said transceiver comprising

an intermediate range optical transmitter responsive to an electrical data input signal for converting said electrical data into an optical output signal for transmission over said intermediate range optical communication system; and

an intermediate range optical receiver, responsive to optical data input from the intermediate range optical communication system and converting said optical data input into a received electrical data signal,

wherein said intermediate range optical transmitter comprises

an electroabsorption modulated laser including an electroabsorption modulator section including a first multiple quantum well active region responsive to the electrical data input signal and

a Fabry-Perot laser section including a second multiple quantum well active region responsive to the electroabsorption modulator for providing a modulated optical output signal,

the Fabry-Perot laser device section and the electroabsorption modulator section forming a monolithic structure having an isolation trench for reducing electrical cross-talk between the laser section and the electroabsorption modulator.

7. An optical transceiver as defined in claim **6** wherein the the Fabry-Perot laser has an operating wavelength of approximately 1310 nm.

8. An optical transceiver as defined in claim **6** wherein the trench has a depth of approximately 0.7 microns.

9. An optical transceiver as defined in claim **6** wherein the electroabsorption modulator is designed to operate in continuous wave mode.

10. An optical transceiver as defined in claim **6** wherein the signals propagate over a communications network having an intermediate range of approximately 10–50 km.

11. An optical transponder module, the module comprising

an intermediate range optical transmitter, responsive to electrical data for converting the electrical data into an optical output signal for transmission,

the intermediate range optical transmitter comprising

an electroabsorption modulated laser including an electroabsorption modulator section responsive to the electrical data and

a Fabry-Perot laser section responsive to the electroabsorption modulator for providing a modulated optical output signal,

the electroabsorption modulator section comprising a first multiple quantum well active region comprising a plurality of barrier layers and a plurality of well layers,

the Fabry-Perot laser device section comprising a second multiple quantum well active region comprising a plurality of barrier layers and a plurality of well layers,

the Fabry-Perot laser device section and the electroabsorption modulator section forming a monolithic structure,

each of the barrier layers and the well layers of the second multiple quantum well region are thicker than each of the barrier layers and the well layers of the first multiple quantum well active region, respectively.

* * * * *

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Simons et al.

(10) **Patent No.: US 6,754,423 B2**
(45) **Date of Patent: Jun. 22, 2004**

(54) **SINGLE MODE OPTICAL FIBRE, AND METHOD FOR THE MANUFACTURE OF A SINGLE MODE OPTICAL FIBRE**

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(73) Assignee: **Draka Fibre Technology B.V.**, Eindhoven (NL)

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(30) **Foreign Application Priority Data**

Jun. 9, 2000 (NL) 1015405

(51) **Int. Cl.**[7] **G02B 6/02**
(52) **U.S. Cl.** **385/126**; 385/127; 385/128
(58) **Field of Search** 385/126, 127, 385/128; 65/3.11, 3.12; 427/39

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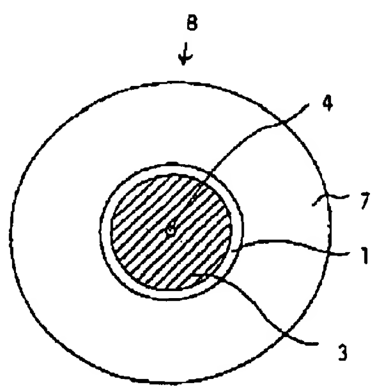
(57) **ABSTRACT**

The present invention relates to a method for the manufacture of a single mode optical fibre comprising a light-conductive core portion, an internal cladding portion surrounding said core portion and a jacketing portion surrounding said internal cladding portion, in which the refractive index of the core portion is larger than those of the cladding and jacketing portion areas, and in which the refractive indices of the cladding and jacketing portion areas are practically equal.

27 Claims, 2 Drawing Sheets



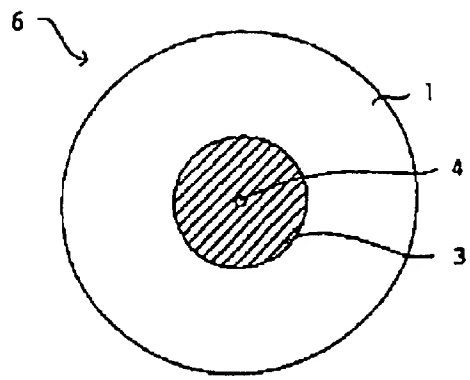


Figure 1

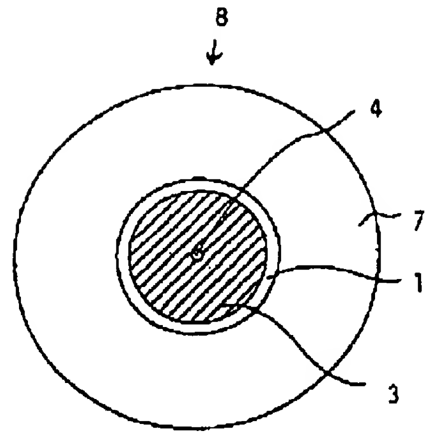


Figure 4

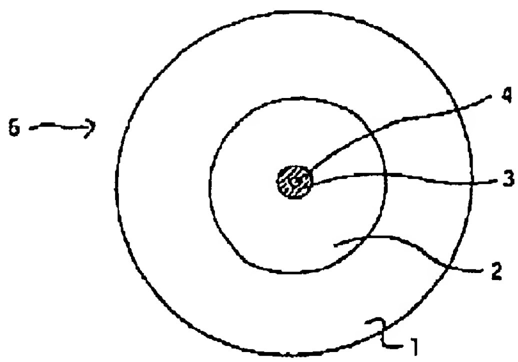


Figure 2

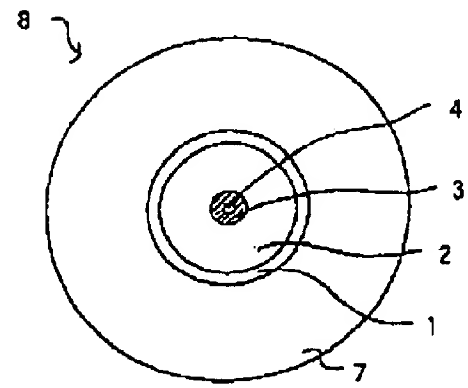


Figure 5

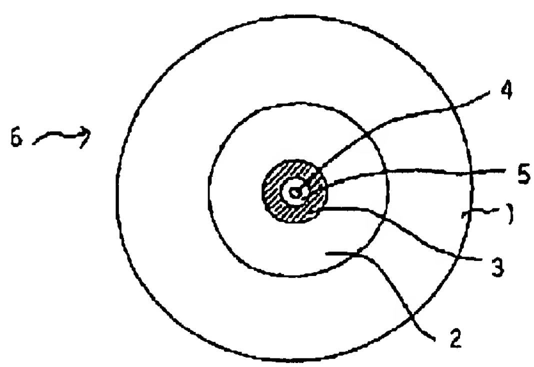


Figure 3

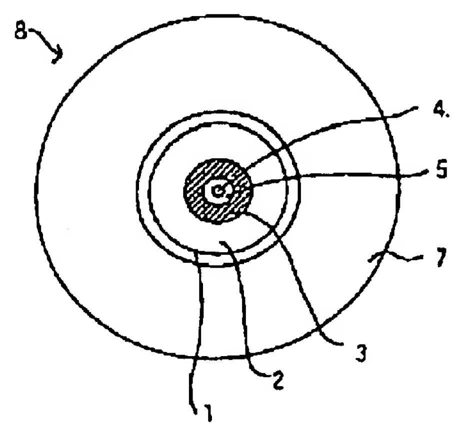


Figure 6

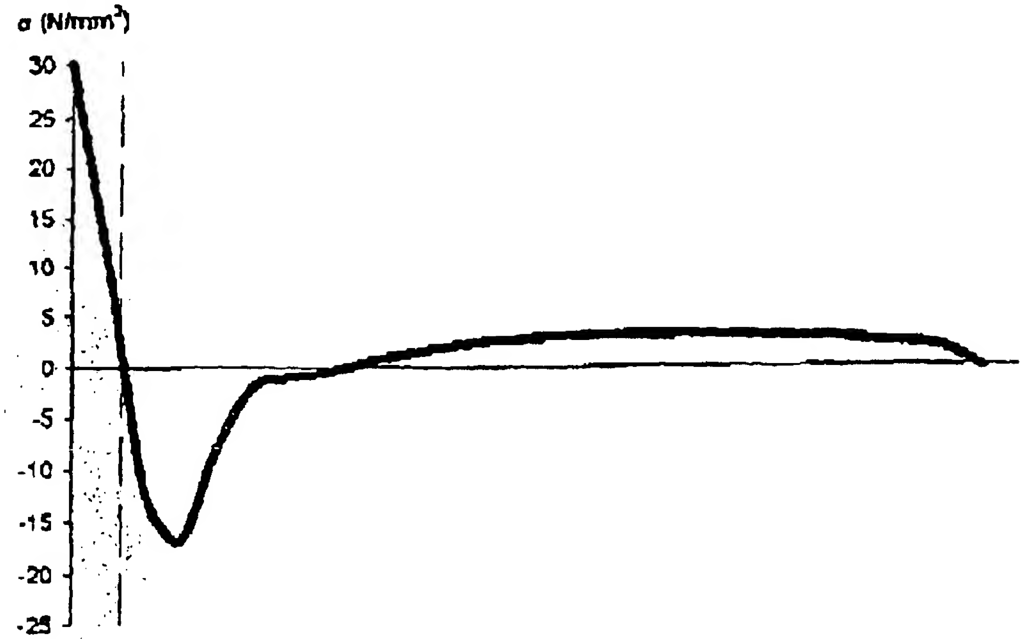


Figure 7

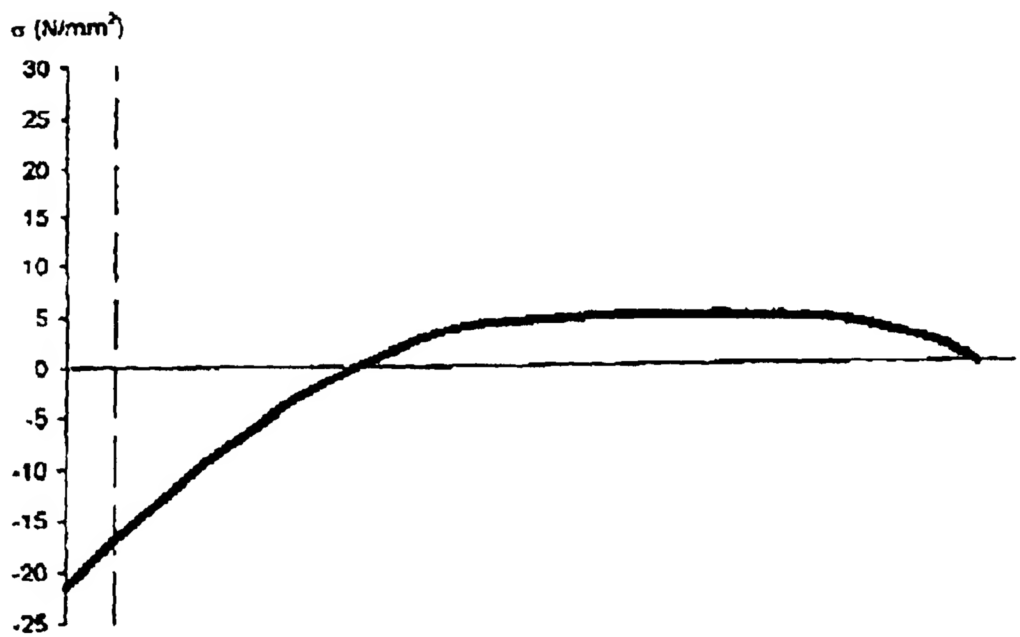


Figure 8

SINGLE MODE OPTICAL FIBRE, AND METHOD FOR THE MANUFACTURE OF A SINGLE MODE OPTICAL FIBRE

The present invention relates to a method for the manufacture of a single mode optical fibre comprising a light-conductive core portion, an internal cladding portion surrounding said core portion and a jacketing portion surrounding said internal cladding portion, in which the refractive index of the core portion is larger than those of the cladding and jacketing portion areas, and in which the refractive indices of the cladding and jacketing portion areas are practically equal, by which method a silica substrate tube used as jacketing portion, is internally flushed with one or more reactive gases to form the internal cladding portion and core portion, respectively, after which the substrate tube thus provided with layers is collapsed and drawn into a single mode optical fibre. Furthermore, the present invention relates to a single mode optical fibre comprising a light-conductive core portion, a cladding portion surrounding said core portion and a jacketing portion surrounding said internal cladding portion.

Optical fibres of this type are well known and are mainly applied in the field of telecommunications technology. See, for example, European Patent Application 0 127 227, U.S. Pat. No. 5,242,476 and U.S. Pat. No. 5,838,866. The term 'single mode' used in the present description is generally known to experts in this field and needs therefore no further explanation here. Because of their characteristic low attenuation and dispersion such optical fibres are particularly suitable for the formation of long-distance data links, often spanning many thousands of kilometers. Over such considerable distances it is of vital importance that the cumulative signal losses in the optical fibre be kept to a minimum, if transmission of optical signals is to occur with a small number of intermediate amplification stations. At the commonly employed transmission wavelength of 1550 nm the telecommunications industry conventionally requires that the total attenuation in such optical fibres does rot exceed 0.25 dB/km, and preferably does not exceed 0.2 dB/km.

Although the presently manufactured fibres may meet all such requirements with regard to permissible attenuation, it is nevertheless often observed that, after elapse of time, the same optical fibres demonstrate considerable attenuation increases, Extensive investigation has shown that this phenomenon is attributable to the gradual seepage of hydrogen gas into the fibre from its surroundings, with the consequent formation of groups like SiH and SiOH within the fibre. These compounds demonstrate strong infra-red absorption, with attenuation peaks at wavelengths of about 1530 and 1385 nm.

A solution to overcome the problem of such hydrogen-induced attenuation is known from European Patent Application 0 477 435. In the method therein disclosed, a molten optical fibre is extensively exposed to a hydrogen-containing gas during its manufacture, so as to ensure that all structural defect sites in the fibre have already been presented with a hydrogen atom before the actual implementation of the fibre. A disadvantage of this known method is, however, that it only addresses the symptoms of hydrogen-induced attenuation and not the causes thereof. Moreover, this known measure considerably complicates the manufacturing process, and introduces an additional risk of contamination of the product fibre by the hydrogen-containing gas employed.

From U.S. Pat. No. 5,090,979 a method for the manufacture of an optical fibre is known, subsequently comprising of a pure silicon dioxide core portion, an outer layer of fluorine-doped silicon dioxide, a substrate layer of fluorine-doped silicon dioxide, and a carrier layer of pure silicon dioxide, in which the refractive index of the core portion is practically equal to that of the carrier layer.

From U.S. Pat. No. 5,033,815 an optical fibre of the multi-mode type is known, which fibre substantially differs from the present single mode optical fibre. Furthermore, the multi, mode optical fibre known from said publication subsequently contains a GeO_2- or Sb_2O_2-doped core portion, an F-doped cladding portion and finally a possibly TiO_2-doped jacketing portion, resulting in the refractive index of the core portion being higher than those of the cladding- and jacketing portion areas, and the refractive index of the jacketing portion being substantially lower than that of the cladding portion, which refractive index profile substantially differs from the present profile. No data with regard to compressive axial stress are known from said publication.

From European Patent Application 0 762 159 a dispersion-compensating fibre is known, subsequently comprising a core portion with at least 10 mol % of GeO_2 and a cladding portion, which cladding portion comprises a first fluorine-doped cladding portion, a second chlorine-doped cladding portion, and a third chlorine- or fluorine-doped cladding portion. The doping of the third cladding portion is chosen such that the glass viscosity at the moment of drawing is lower than that of pure silicon dioxide glass, which allows a relatively low temperature during drawing. No data with regard to compressive axial stress are known from this application.

It is therefore an objective of the present invention to provide a method for the manufacture of a single mode optical fibre, in which the hydrogen-induced attenuation at a wavelength of 1550 nm is sufficiently low to ensure the total attenuation at that wavelength to be at most 0.25 dB/km, and preferably to be at most 0.2 dB/km.

As mentioned in the preamble, in accordance with the present invention this objective is achieved because the present method for the manufacture of a single mode optical fibre is characterised in that the internal cladding portion is built up from SiO_2 comprising a fluorine doping within a range of 0.1–8.5 wt. %, thus resulting in the core portion to be subjected to a compressive axial stress over its full cross section.

The present inventors suppose that the presence of axial compression in the fibre core prevents the occurrence of the defects mentioned before, thus resulting in a significantly lowered hydrogen-induced attenuation. Since, according to the present inventors, the presence of axial tension in a fibre core facilitates the formation of structural defects in the silicon dioxide core, the presence of axial compression in a fibre core will essentially inhibit the occurrence of such defects, thus leading to a substantially lowered hydrogen-induced attenuation.

The present inventors have carried out a number of experiments in which a preform was manufactured by subsequently providing the internal surface of a substrate tube with an internal cladding portion of silicon oxide, which cladding portion is built up of SiO_2, comprising fluorine-doping, and a second doped layer of silicon oxide, which second layer has a higher refractive index than that of the internal cladding portion and forms the final core of the fibre. The substrate tube thus provided with a core portion and internal cladding portion was subsequently thermally subjected to a collapse procedure to form a rod, which rod eventually was drawn into the required fibres at one of its molten extremities.

In the present invention the internal cladding portion is preferably doped with fluorine within a range of 0.1–8.5 wt. %, and preferably of 0.2–2.0 wt. %. Fluorine-doping of more than 8.5 wt. % is undesirable since then problems will arise in the deposition of such layers. A fluorine amount of less than 0.1 wt. % does not give a noticeable result with regard to the required compressive axial stress in the core portion. A maximum doping of 2.0 wt. % is particularly preferred if very low attenuation losses are required, which attenuation losses are negatively influenced by the increase of Rayleigh scattering. The fact is that experiments have shown that part of the internal cladding portion also functions as a light path for the light that is transported inside the fibre's core.

The application of fluorine doping in the internal cladding portion results in a decrease of the refractive index of this layer. In order to adjust the thus lowered refractive index, which refractive index preferably is practically equal to that of the jacketing portion area, the internal cladding portion is provided with so-called refraction-increasing doping materials, like, for instance, P_2O_5, TiO_2, ZrO_2, SnO_2, GeO_2, N or Al_2O_3, or a combination of one or more of such compounds.

In certain embodiments of the present method it is particularly preferred to insert a buffer layer between the jacketing portion and the internal cladding portion, which buffer layer has a refractive index that is lower than that of the core portion and is practically equal to that of the cladding portion and jacketing portion areas.

Such a buffer layer is particularly required if the optical quality of the jacketing portion is low, which means that the jacketing portion contains impurities. In the successive heat treatments for the collapse for manufacturing the preform and the subsequent drawing of fibres from the preform, such impurities may diffuse to the light-conductive part of the optical fibre, as a result of which a heightened attenuation occurs. The application of a buffer layer therefore prevents the impurities to end up in the light-conductive part of the fibre.

In a special embodiment of the present method it is also preferred to insert an intermediate layer between the core portion and the internal cladding portion, which intermediate layer has a refractive index that is lower than that of the core portion and is practically equal to that of the internal cladding and jacketing portion areas.

The light conduction in the single mode optical fibre partially occurs in the layer directly surrounding the core portion. If this layer is heavily doped, effects of increased Rayleigh scattering are noticeable, leading to an attenuation increase. However, high doping may be required to bring the core portion, under the required compressive axial stress. Thus an intermediate layer with low doping is preferably inserted to prevent possible negative effects of extra Rayleigh scattering.

The internal cladding portion preferably has a thickness 3–21 micrometers in the final fibre.

The required layer thickness depends on the dopings in the layer. Tests have shown that a layer thickness of less than 3 micrometers is insufficient to bring the core portion under the required compressive axial stress, which is required in accordance with the present invention. The upper limit of the maximum layer thickness for the internal cladding portion is mainly determined by the processability of the preform that is eventually drawn into an optical fibre.

In a certain embodiment it is furthermore required that the light-conductive core portion provided with one or more dopings is built up of SiO_2, comprising a fluorine doping within a range of 0.2–2 wt. % and one or more dopings that ensure the core portion to possess the refractive index required in accordance with the present invention, which core refractive index is higher than that of the cladding portion, which dopings, for instance, may comprise P_2O_5, TiO_2, ZrO_2, SnO_2, GeO_2, N and Al_2O_3 or a combination of one or more of these compounds.

In a special embodiment it is preferred that the preform, comprising the core portion, internal cladding portion and jacketing portion, possibly supplemented with a buffer and/or intermediate layer, at the outer surface of the jacketing portion is provided with an additional layer, for instance in the form of a glass tube or a layer applied by means of an external CVD procedure.

In accordance with the present invention the formation of the core portion and internal cladding portion, and possibly the intermediate and/or buffer layer mentioned before, is carried out by means of a chemical vapour deposition procedure, in particular with a PCVD procedure, preferably plasma-induced. Since the axial length of a conventional substrate tube in particular is many times larger than its diameter, a controlled deposition of a uniform layer of material onto the internal surface of such a substrate tube is very hard to achieve with the conventional deposition procedures like sputter deposition or laser ablation deposition. In the PCVD embodiment the applied chemical vapour can successfully be distributed over the full length of the internal surface of the substrate tube, thus enabling a very uniform deposition onto the internal wall. Moreover, by applying the PCVD procedure it is possible to carry out a deposition of layers with controlled doping levels, thus enabling this procedure to be used successfully for the deposition of the core portion and internal cladding portions possibly supplemented with the intermediate and/or buffer layers.

The present invention further relates to a single mode optical fibre comprising a light-conductive core portion, an internal cladding portion surrounding said core portion and a jacketing portion surrounding said internal cladding portion, in which the refractive index of the core portion is larger than that of the internal cladding portion and jacketing portion areas, and in which the refractive indices of the internal cladding portion and jacketing portion areas are practically equal, which single mode optical fibre in accordance with the present invention is characterised in that the internal cladding portion is built up of SiO_2 comprising a fluorine doping within a range of 0.1–8.5 wt. %, preferably of 0.2–2.0 wt. %, resulting in the core portion being subjected to a compressive axial stress over its full cross section.

In a special embodiment it is further preferred that the single mode optical fibre is built up in such a way that between the core portion and the internal cladding portion an intermediate layer is inserted, which intermediate layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

Moreover, in a special embodiment of the present single mode optical fibre it is preferred that there is a buffer layer between the jacketing portion and the internal cladding portion, which buffer layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

Furthermore, in certain embodiments it is preferred that there is an external cladding portion on the outside of the jacketing portion.

Below, the present invention is illustrated by means of a number of drawings, which drawings only serve an illus-

trated purpose and do not form any limitation to the scope of protection of the present invention.

FIG. **1** represents an embodiment of a single mode optical fibre in accordance with the present invention.

FIG. **2** represents a special embodiment of a single model optical fibre in accordance with the present invention, in which a buffer layer has been placed.

FIG. **3** represents a special embodiment of a single model optical fibre in accordance with the present invention, in which an intermediate layer has been placed.

FIGS. **4**–**6** correspond to the respective FIGS. **1**–**3**, in which the jacketing portion, however, has been provided with an external cladding portion.

FIG. **7** represents a graph of tension vs. fibre radius in accordance with the state of the art.

FIG. **8** represents a graph of tension vs. fibre radius in accordance with the present invention.

In FIG. **1** a single mode optical fibre **6** is schematically represented, which optical fibre **6** has been obtained after collapsing a preform and the drawing from it of a fibre. The single mode optical fibre **6** can been regarded as a light-conductive core portion **4**, which light-conductive core portion **4** is surrounded by an internal cladding portion **3**, in which the internal cladding portion **3** is subsequently surrounded by a jacketing portion **1**. A substrate tube is, for instance, suitable as jacketing portion. The refractive index of the core portion **4** is larger than the refractive indices of the internal cladding portion **3** and the jacketing portion **1**, in which the refractive indices of the last two portions are practically equal. It should be mentioned that the same reference numbers used in FIGS. **1**–**6** correspond with one another.

In FIG. **2** a special embodiment of the single mode optical fibre **6** is schematically represented, which single mode optical fibre **6** comprises a light-conductive core portion **4**, which light-conductive core portion **4** is surrounded by an internal cladding portion **3**, which internal cladding portion **3** is surrounded by a buffer layer **2**, which buffer layer **2**, finally, is surrounded by a jacketing portion **1**. Such a single mode optical fibre **6** is manufactured in accordance with the present method by using a silica substrate tube as jacketing portion **1**, after which buffer layer **2**, internal cladding portion **3** and finally core portion **4**, respectively, are deposited by means of a PCVD procedure. When the aforementioned layers have been deposited onto the silica substrate tube, a thermal collapse procedure is carried out after which a preform is obtained from which in the end the single mode optical fibre **6** is drawn.

In FIG. **3** a special embodiment of the single mode optical fibre **6** is schematically represented, which single mode optical fibre **6** comprises a core portion **4** surrounded by an intermediate layer **5**, which intermediate layer **5** is surrounded by an internal cladding portion **3**, which internal cladding portion **3** is surrounded by a buffer layer **2**, which buffer layer **2**, finally, is surrounded by a jacketing portion **1**. The single mode optical fibre **6** schematically represented in FIG. **3** is manufactured in the same manner as is described in FIG. **2**. In certain embodiments it is, however, also possible to omit the buffer layer **2** shown in FIG. **3**, resulting in the internal cladding portion **3** to be directly deposited onto the jacketing portion **1**, followed by intermediate layer **5** and finally core portion **4**. However, this embodiment is not schematically represented.

In FIG. **4** the jacketing layer **1** is provided with an external cladding portion **7**, which also applies in FIGS. **5** and **6**. The present invention should especially be seen in the subjection of the core portion of a single mode optical fibre to compressive axial stress by doping the internal cladding portion with fluorine in a range of 0.1–8.5 wt. %, and preferably of 0.2–2.0 wt %.

In FIG. **7** a graph is shown of the stress (as function of the radius r of a single mode optical fibre in accordance with the state of the art, which fibre is composed of a core portion built up of SiO2 doped with GeO2 and F, and an undoped cladding portion composed of SiO2. The position of the core portion is indicated by a vertical dotted line, and is thus it is immediately clear that the core portion is under a positive stress, namely a tensile stress.

In FIG. **8** a graph is shown of the stress (as function of the radius r of a single mode optical fibre in accordance with the present invention, which fibre is composed of a core portion built up of SiO2 doped with GeO2 and F, and further an internal cladding portion, which is built up of SiO2 doped with F and GeO2 in accordance with FIG. **5**, possesses, in which the remaining areas consist of undoped SiO2. The position of the core portion is also indicated by a vertical dotted line, and it is immediately noticeable that the core portion is under an compressive axial stress, which is required in accordance with the present invention.

What is claimed is:

1. A single mode optical fibre comprising:

a light-conductive core portion,

an internal cladding portion surrounding this core portion, and

a jacketing portion surrounding this internal cladding portion, in which the refractive index of the core portion is larger than those of the cladding portion and jacketing portion areas and in which the refractive indices of the cladding portion and jacketing portion areas are practically equal,

wherein the internal cladding portion is built up of SiO_2 comprising a fluorine doping within a range of 0.1–8.5 wt. %, thus resulting in the core portion to be subjected to a compressive axial stress over its full cross section.

2. A single mode optical fibre according to claim **1**, wherein the amount of fluorine in the internal cladding portion (**3**) lies within the range of 0.2–2.0 wt. %.

3. A single mode optical fibre according to claim **1**, further comprising a buffer layer between the jacketing portion and the internal cladding portion, which buffer layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

4. A single mode optical fibre according to claim **1**, further comprising an intermediate layer between the core portion and the internal cladding portion, which intermediate layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

5. A single mode optical fibre according to claim **1**, further comprising an external cladding portion on the outside of the jacketing portion, which external cladding portion has a refractive index that is practically equal to those of the internal cladding portion and jacketing portion areas.

6. A single mode optical fibre according to claim **1**, wherein the internal cladding portion has a thickness that lies within the range of 3–21 μn.

7. A single mode optical fibre according to claim **1**, wherein the core portion is built up of SiO_2 comprising fluorine doping within a range of 0.2–2.0 wt. %.

8. A method for the manufacture of a single mode optical fibre, comprising a light-conductive core portion, an internal cladding portion surrounding this core portion and a jacketing portion surrounding this internal cladding portion, in

which the refractive index of the core portion is larger than those of the internal cladding portion and jacketing portion areas, and in which the refractive indices of the internal cladding portion and jacketing portion areas are practically equal, according to which method a silica substrate tube, functioning as jacketing portion, is being flushed with one or more reactive gases to form the internal cladding portion and the core portion, respectively, after which the substrate tube is collapsed and is drawn into a single mode optical fibre, characterised in that the internal cladding portion is built up of SiO_2 comprising of fluorine doping within a range of 0.1–8.5 wt. %, thus resulting in the core portion to be subjected to a compressive axial stress over its full cross section.

9. A method according to claim **8**, wherein the amount of fluorine in the internal cladding portion lies within the range of 0.2–2.0 wt. %.

10. A method according to claim **8**, wherein a buffer layer is inserted between the jacketing portion and the internal cladding portion, which buffer layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

11. A method according to claim **8**, wherein an intermediate layer is inserted between the core portion and the internal cladding portion, which intermediate layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

12. A method according to claim **8**, wherein on the outside of the jacketing portion an external cladding portion is placed, which external cladding portion has a refractive index that is practically equal to those of the internal cladding portion and jacketing portion areas.

13. A method according to claim **8**, that wherein the formation of the core portion, and the internal cladding portion, and possibly of the external cladding portion, the intermediate layer and/or buffer layer, is carried out by a PCVD procedure.

14. A method according to claim **13**, wherein the PCVD procedure is carried out under plasma induction.

15. A single mode optical fibre comprising:

a light-conductive core portion,

an internal cladding portion surrounding this core portion, and

a jacketing portion surrounding this internal cladding portion, in which the refractive index of the core portion is larger than those of the cladding portion and jacketing portion areas and in which the refractive indices of the cladding portion and jacketing portion areas are practically equal,

wherein the internal cladding portion is built up of SiO_2 comprising a fluorine doping within a range of 0.1–8.5 wt. %, thus resulting in the core portion to be subjected to a compressive axial stress over its full cross section, and characterised in that the attenuation loss of the fibre is at most 0.25 dB/km at 1550 nm.

16. A single mode optical fibre according to claim **15**, wherein the amount of fluorine in the internal cladding portion lies within the range of 0.2–2.0 wt. %.

17. A single mode optical fibre according to claim **15**, further comprising a buffer layer between the jacketing portion and the internal cladding portion, which buffer layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

18. A single mode optical fibre according to claim **15**, further comprising an intermediate layer between the core portion and the internal cladding portion, which intermediate layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

19. A single mode optical fibre according to claim **15**, further comprising an external cladding portion on the outside of the jacketing portion, which external cladding portion has a refractive index that is practically equal to those of the internal cladding portion and jacketing portion areas.

20. A single mode optical fibre according to claim **15**, wherein the internal cladding portion has a thickness that lies within the range of 3–21 μm.

21. A method for the manufacture of a single mode optical fibre, comprising a light-conductive core portion, an internal cladding portion surrounding this core portion and a jacketing portion surrounding this internal cladding portion, in which the refractive index of the core portion is larger than those of the internal cladding portion and jacketing portion areas, and in which the refractive indices of the internal cladding portion and jacketing portion areas are practically equal, according to which method a silica substrate tube, functioning as jacketing portion, is being flushed with one or more reactive gases to form the internal cladding portion and the core portion, respectively, after which the substrate tube is collapsed and is drawn into a single mode optical fibre, characterised in that the internal cladding portion is built up of SiO_2 comprising of fluorine doping within a range of 0.1–8.5 wt. %, thus resulting in the core portion to be subjected to a compressive axial stress over its full cross section, and characterised in that the attenuation loss of the fibre is at most 0.25 dB/km at 1550 nm.

22. A method according to claim **21**, wherein the amount of fluorine in the internal cladding portion lies within the range of 0.2–2.0 wt. %.

23. A method according to claim **21**, wherein a buffer layer is inserted between the jacketing portion and the internal cladding portion, which buffer layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

24. A method according to claim **22**, wherein an intermediate layer is inserted between the core portion and the internal cladding portion, which intermediate layer has a refractive index that is lower than that of the core portion and is practically equal to those of the internal cladding portion and jacketing portion areas.

25. A method according to claim **21**, wherein on the outside of the jacketing portion an external cladding portion is placed, which external cladding portion has a refractive index that is practically equal to those of the internal cladding portion and jacketing portion areas.

26. A method according to claim **21**, wherein the formation of the core portion, and the internal cladding portion, and possibly of the external cladding portion, the intermediate layer and/or buffer layer, is carried out by means of a PCVD procedure.

27. A method according to claim **26**, wherein the PCVD procedure is carried out under plasma induction.

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